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Assessment of Environmental Fate and Effects of Discharges from Offshore Oil and Gas Operations

Technical Resources, Inc., Rockville, MD

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16. ABSTRACT

The overall objectivies of this study are to characterize and assess the fate and effects of discharges from offshore oil and gas drilling and production activitied. Four specific objectives were outlines by EPA:

- o Present overall conclusions on the fate and effects of drilling fluids and cuttings discharged to the marine environment,
- o Describe types and quantities from offshore drilling and production
- o Describe transport phenomena to which discharges will be subjected, including physical, chemical, and biological processes. and
- o Present information on the acute and chronic toxicity of drilling fluids and produced waters on marine organisms

Section 1 presents background information on offshore drilling and production processes and associated discharges. Section 2 details discharge characteristics and composition, and quantifies discharge volumes; especially for drilling fluids cuttings and produced water. Section 3 describes the environmental fate of discharges, including physical, chemical, and biological pathways. Toxicity information on drilling muds and produced waters is presented in Section 4. Section 5 presents summaries of field studies of particular interest regarding drilling and production activity. Section 6 presents information on the ecological resource characteristics of shallower marine environments. Section 7 presents the findings and conclusions.

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ASSESSMENT OF ENVIRONMENTAL FATE AND EFFECTS OF DISCHARGES FROM OFFSHORE OIL AND GAS OPERATIONS

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EXECUTIVE SUMMARY

This report has reviewed and evaluated available information on the composition, fate, and effects of the major discharges (drilling fluids, cuttings, and produced water) from offshore oil and gas platforms. Based on the review of a substantial body of data, a large number of conclusions were reached, as presented below. Notwithstanding the large data base, datagaps and other factors contribute to a substantial uncertainty in these conclusions. Thus, most conclusions here are qualified.

DRILLING FLUIDS AND CUTTINGS

Drilling fluids are slurries with a high solids content (25 to 75 percent w/w), largely due to their barite ($BaSO_4$) and clay components. Drilling fluids also contain a large variety of inorganic materials. To date, most attention has focused on the effects of toxics. However, very few studies have analyzed for toxics other than metals. Only one study has reported a priority pollutant screen, in which pesticides were not included. Fewer analyses have been conducted on cuttings. The conclusions reached for drilling fluids and cuttings in this report are as follows.

1. Acute lethal toxicity of drilling muds appears to be correlated to added mineral or diesel oil, and Biochemical Oxygen Demand (BOD). Diesel oil is a particularly toxic component of drilling fluids. In studies to date, mineral oil is less toxic (some 3- to 7-fold), but still is a substantial contributor to the toxicity of drilling fluids. Adding diesel oil to any

mud produced a strong correlation with toxicity. Toxicity also correlated well with diesel oil equivalents (equivalent to API #2 fuel oil) in the suspended particulate phase for nongeneric muds, but somewhat less well with levels of aliphatics and aromatics. Diesel oil equivalents, aliphatics, and aromatics in whole muds generally correlated somewhat less well with toxicity than did added oil in whole muds. Toxicity of generic muds shows a very strong correlation with BOD. Due to a lack of BOD data no such correlation was possible for nongeneric muds. Other factors, such as acidity and particle size, may contribute to toxicity. Such contributions cannot be assessed based on available data/methodology. Bulk metals content appears to have a very low correlation to acute lethal drilling mud toxicity, with the possible exception of a weak correlation to chromium.

2. Based upon one Environmental Protection Agency (EPA) study, in which a priority screen excluding pesticides was conducted, only a single organic was detected in generic drilling muds to which no oil had been added. Toxic organics in drilling muds most probably would be due to addition of mineral or diesel oils and/or certain other additives, such as biocides. Many metal priority pollutants, including antimony, arsenic, cadmium, lead, and mercury were detected in both generic and nongeneric muds. Metal levels in nongeneric muds were, in general, at least one order of magnitude higher than those in generic muds.

3. A major new finding in this assessment is that drilling fluids contain high levels of 5-day Biochemical Oxygen Demand (BOD_5) as well as 20-day Ultimate Oxygen Demand (UOD_{20}), and Chemical Oxygen Demand (COD). A median scenario estimate (average mass load x average concentration) of the BOD measured in muds and cuttings is 33 tons (kkg) per well drilled. For the 1464 wells drilled in 1982, this represents a total of 49,200 tons of BOD per year. These BOD estimates are likely to be underestimates of actual BOD because the toxicity of added oil reduces measured BOD. Total Chemical Oxygen Demand (COD) averaged 308 tons/well or 451,000 tons annually. Total BOD from the muds and cuttings from the offshore oil and gas industry is more than six times higher than the total BOD of ocean dumped municipal sewage sludge, although some 3.5-fold more sludge is disposed on a mass basis. The total COD of discharged drilling fluids and cuttings is more than 30 times higher than the COD of all U.S. ocean dumped sewage sludge. Over 60 percent of this oxygen demand is estimated to be discharged in Louisiana state waters.

4. Barite, the main component of most drilling fluids, has a very high specific gravity (4.2 g/ml). As a result, most barite settles out of the lower plume and deposits in sediments. Such deposits may become significant over time, particularly in low-energy areas or in high energy areas with intensive drilling activities. The small particle size of the barite can cause physical effects, including substrate alteration, suffocation, and/or abrasion of gills.

Heavy metals, such as cadmium, copper, antimony, arsenic, lead, nickel, and mercury are associated with barite, although they may also be associated with other drilling fluid additives. Barite may represent a significant contribution to heavy metal loadings of sediments because it can comprise up to 70 percent of drilling muds by weight.

Calcium, aluminum, and iron concentrations also can be very high, i.e., in the percentage range. Mercury concentrations were uniformly low in generic muds (no data were available for nongeneric muds), although certain types of barite showed high excursions in mercury and a variety of other associated trace metal levels. Cadmium and chromium levels were low in generic muds compared to nongeneric muds. Most of these metals can be enriched in sediments around drilling platforms and also show the potential for bioaccumulation in laboratory studies and field surveys.

Although, the significance of potential toxic (including bioaccumulation) and physical effects of particle deposition is not fully understood, deposition represents a potential source of chronic, sublethal impacts. At a workshop to model potential impact, no "worst case" scenario could be developed, based on available data and assessment methodologies. While the risks from exploratory operations appear to be limited, risks from intense drilling operations are not yet quantifiable.

5. Several reviews of the literature on discharges from offshore oil and gas activities have been completed. There is general agreement among these with regard to quantities of material discharged and toxicity. This report has pointed out that there yet exists a lack of understanding of the actual cause(s) of toxicity, that one major factor, BOD, may have been overlooked, and that toxicity test protocols and the unanticipated use of lubricating/spotting oils may result in a substantial underestimation of toxicity. Another uncertainty arises from the extrapolation of single species tests to assessments of overall effects.

6. Data on one-well operations are adequate to predict with reasonable assurance that such activities result in limited impacts within the limits of resolution of existing studies. This review, however, does not consider the current data base sufficient to evaluate potential impacts from intensive exploration or development activities. This concern is exacerbated by the absence of any on-going or mandatory monitoring program to address this concern. There have been only two studies on fluid discharges from single exploratory wells that are based on satisfactory statistical and field sampling methods (i.e., that were capable of detecting changes of less than approximately 100 percent). There has been no adequate study of an exploratory well in a shallow, low-energy environment. More importantly, there have been no benthic studies on the effects of discharges from a development platform, involving a large number of wells, in any type of environment. Thus, in the

absence of a satisfactory data gathering effort, the potential risk of serious impacts may be high, for intensive drilling activities, in vulnerable or valuable areas. Such areas include shallow waters, poorly flushed waters, waters subject to other sources of anthropogenic or natural episodic stress, and hard bottom areas.

PRODUCED WATER

One of the issues related to regulating produced water discharges is the uncertainty about the nature and extent of effects. Some of this uncertainty (e.g., chronic effects of produced water discharges) could be dealt with through focused long-term studies. The following summarize the key observations that have led to environmental concerns regarding ocean discharge of produced waters:

1. Produced waters contain elevated concentrations of certain petroleum hydrocarbons. In particular, lighter aromatics (benzene through naphthalene) are present. These are among the more acutely toxic petroleum hydrocarbons. Toxicity tests on produced waters (without biocides), and water soluble fractions of crude oil, which contain similar concentrations of light aromatic hydrocarbons, generally indicate that the acute lethal toxicity of produced water is low. However, some portion of the volatile toxic components is lost upon collection and shipment of samples and upon aeration of the test media (which was required to maintain dissolved oxygen levels above 4 ppm).

2. Produced waters often contain various chemical additives, although there is limited information on the presence and quantities of these chemicals in the discharge. These chemicals, which include biocides used to control the growth of bacteria, can greatly increase the toxicity of produced waters. This has been revealed by laboratory toxicity tests and by cage experiments in the field. Reports on divers working near a produced water discharge that contained the biocide acrolein also are informative: the divers reported eye and skin irritations that were severe enough to interrupt their activities.

3. There is clear evidence that hydrocarbons in produced water discharges can exert chronic lethal effects on benthic organisms around production platforms. This was apparent for a relatively long-term, high volume discharge at the shallow water (2.5 m) Trinity Bay site and also for the relatively long-term, low volume discharge in the deeper water (20 m) Buccaneer Field site. The full spatial extent of chronic effects of produced water discharges on benthos is difficult to delineate from these studies because of the generally elevated levels of hydrocarbons in sediments. This creates a "signal to noise" problem with respect to detecting effects of individual discharges.

4. Available information, in addition to the studies noted above, suggests that shallow, coastal environments are more vulnerable to effects of produced water than deeper offshore areas. A recent American Petroleum Institute (API) report notes that transport of contaminants from the air/sea interface to the sediments will be more efficient in shallower coastal waters than offshore. In addition, the higher turbidities characteristics of coastal waters would also be conducive to sedimentation of contaminants.

5. The input of petroleum hydrocarbons (in particular aromatics) could contribute to chronic pollution of the water column. Although, the chemicals may be rapidly mixed and dispersed upon entering the marine environment, there is evidence that coastal waters of Louisiana contain elevated levels of the volatile liquid hydrocarbons characteristic of produced waters. There are undoubtedly other sources of these hydrocarbons as well, but concentrations are higher around production platforms as evidenced by studies at the Buccaneer Field. These concentrations are at levels that could result in sublethal effects.

   Transport to sediments is also a concern. The Trinity Bay study, for example, noted that effluent concentrations of naphthalenes (1.6 mg/liter) were diluted rapidly (2000-fold at approximately 15 m). Therefore, at the 15 m sampling site water column concentrations would be calculated at 0.8 μg/liter, while sediment concentrations of the site were elevated to 20 mg/kg at the (sediment) surface and over 40 mg/kg at some subsurface depths.

6. There have been several reviews that have attempted to place various sources of petroleum hydrocarbons in perspective through comparisons with other sources (river discharge, tankers, oil seeps). Generally, these show that produced water discharges contribute a comparatively small percentage of the overall input on an ocean-wide or world-wide basis. Two factors must be considered with respect to this conclusion and with regard to the regulation of this discharge. First, although the relative contribution is small, the discharge should not necessarily be ignored: there are numerous instances where individual industrial discharges are "small" but collectively contribute to overall incremental pollution to the environment. Second, discharges of produced water can exert environmental effects at the local or regional level.

7. Produced waters contain other materials that are of potential environmental concern. Radioactive materials such as radium are found in some oil field produced waters. The activity of these may be four orders of magnitude greater than that of open ocean waters. Other inorganics that may be present based on limited data, include heavy metals, ammonia, hydrogen sulfide, and various oxygen consuming substances.

   Very high BOD levels were noted in one study of produced water in southern California. Based on these BOD levels, localized decreases in oxygen content were predicted to occur. From the BOD levels observed in this study and from industry estimates of produced water volumes in the Gulf of Mexico, where a major portion of offshore structures is located, the BOD load from produced water in the Gulf of Mexico was calculated to be 37,000 tons per year.

1.0 INTRODUCTION

The United States Environmental Protection Agency (EPA) has prepared this study as part of the development of New Source Performance Standards (NSPS) and Best Available Technology (BAT) regulations for marine discharges from offshore oil and gas drilling and production operations under the authority of Sections 301, 304, and 306 of the Clean Water Act (CWA). Excluded from consideration in the study are potential impacts from oil spills, marine transportation, and pipelines, which are covered under other sections of the CWA. Within EPA, the proposed regulations are being developed by the Office of the Water Regulations and Standards (OWRS). In support of this effort this assessment will evaluate the discharges, environmental fate, and potential environmental effects associated with this industrial category.

1.1 REPORT OBJECTIVES AND METHODOLOGY

The overall objectives of this study are to characterize and assess the fate and effects of discharges from offshore oil and gas drilling and production activities. Four specific objectives were outlined by EPA:

- Present overall conclusions on the fate and effects of drilling fluids and cuttings discharged to the marine environment

- Describe types and quantities of discharges from offshore drilling and production operations

- Describe transport phenomena to which discharges will be subjected, including physical, chemical, and biological processes

- Present information on the acute and chronic toxicity of drilling fluids and produced waters on marine organisms

Some of the major references consulted for this report were: "Environmental Assessment of Drilling Fluids and Cuttings Released onto the Outer Continental Shelf for the Gulf of Mexico" (Petrazzuolo, 1981; 1983); "Fate and Effects of Drilling Fluids and Cuttings Discharges in Lower Cook Inlet, Alaska, and on Georges Bank" (Houghton et al., 1981); "Proceedings of the Symposium on Environmental Fate and Effects of Drilling Fluids and Cuttings" (American Petroleum Institute, 1980); "Drilling Discharges in the Marine Environment" (National Research Council, 1983); "A Study of Environmental Effects of Exploratory Drilling on the Mid-Atlantic Outer Continental Shelf" - (EG & G, 1982); "Effects of Oil Field Brine Effluent on Benthic Organisms in Trinity Bay, Texas" (Armstrong et al., 1977); "Georges Bank Benthic Infauna Monitoring Program" (Blake et al., 1983); "Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, 1978-1979" (National Marine Fisheries Service, 1980). "Ecological Effects of Produced Water Discharges for Offshore Oil and Gas Production Platforms" (Middleditch, 1984), and "Results of the Drilling Fluids Research Program sponsored by the Gulf Breeze Environmental Research Laboratory, 1976-1984, and Their Application to Hazard Assessment" (Duke and Parrish, 1984). Numerous other documents were also reviewed as discussed in the sections and as listed in the References section, and all information was integrated to create a single comprehensive report.

Section 1 presents background information on offshore drilling and production processes and associated discharges. Section 2 details discharge characteristics and composition, and quantifies discharge volumes; especially for drilling fluids, cuttings and produced water. Section 3 describes the environmental fate of discharges, including physical, chemical, and biological pathways. Toxicity information on drilling muds and produced waters is presented in Section 4. Section 5 presents summaries of field studies of particular interest regarding drilling and production activity. Section 6 presents information on the ecological resource characteristics of shallower marine environments. Section 7 presents the findings and conclusions.

1.2 OVERVIEW OF OFFSHORE DRILLING

Drilling activity on the outer continental shelf (OCS) has been conducted with increasing frequency since the early 1950's, when drilling was confined primarily to the Louisiana and Texas coasts. Since that time, drilling has expanded to include the Atlantic, Pacific, and Alaskan coasts. This increase in drilling activity can be seen in Figure 1-1. Table 1-1 compares the number of producing and non-producing OCS leases for the years 1954 and 1980. Most new wells today are being drilled in the Gulf of Mexico, with other activity off Alaska, California, and in the Atlantic (Table 1-2).

Figure 1-1
Outer Continental Shelf
Drilling Activity, 1954-1980 (USGS,1981)

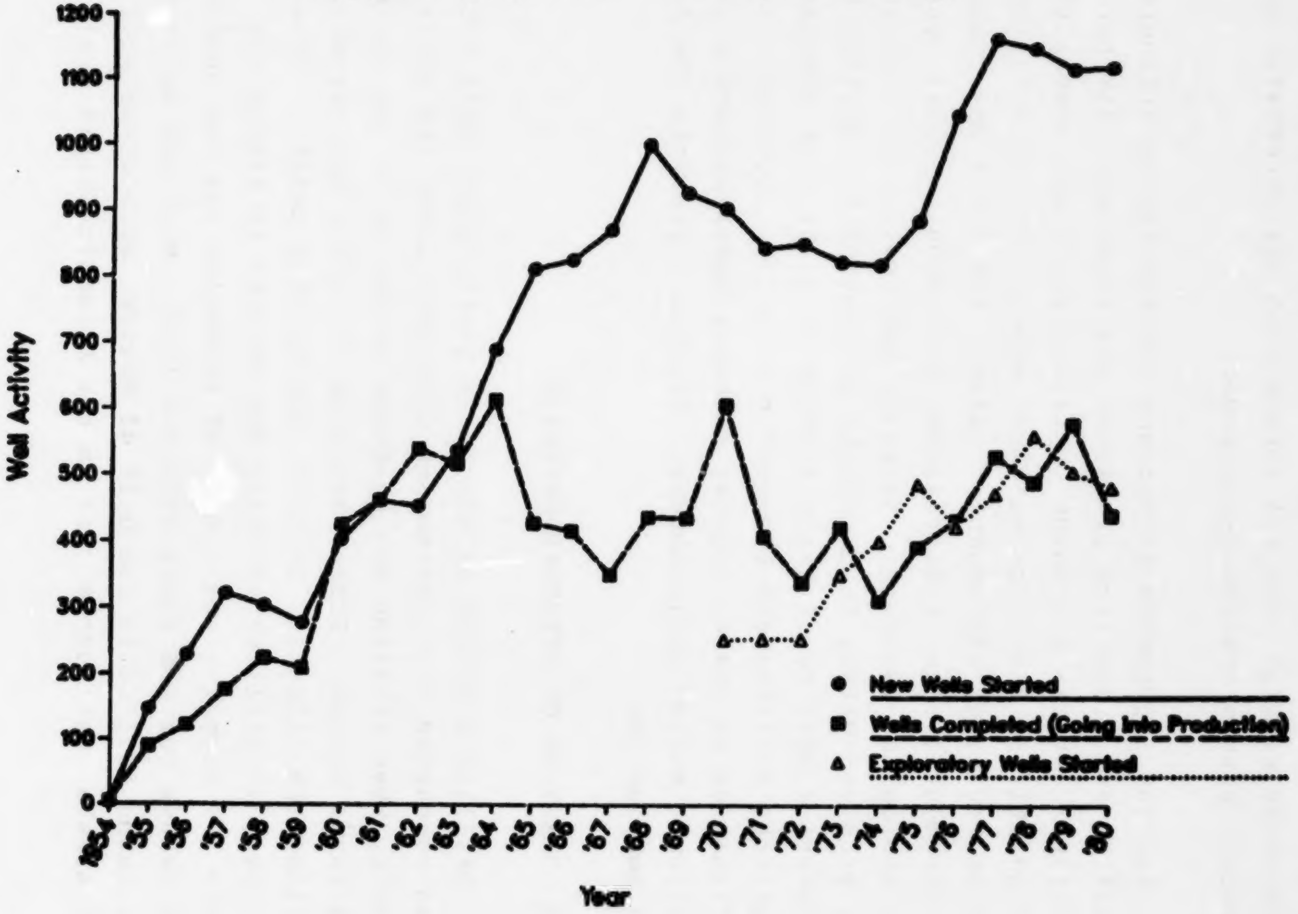

TABLE 1-1 OUTER CONTINENTAL SHELF
PRODUCING AND NON-PRODUCING LEASES (OIL, GAS, SALT AND SULFUR) FOR CALENDAR YEARS 1954 AND 1980 ONLY
(USGS, 1981)

Year of activity	Activity during calendar year					
	Producing		Non-producing		Total	
Adjacent state	Number	Acreage	Number	Acreage	Number	Acreage
1954						
Louisiana	58	240,028	295	1,066,739	353	1,306,767
Louisiana-Sulfur	-	-	5	25,000	5	25,000
Texas	-	-	120	196,926	120	196,926
TOTAL ACTIVITY DURING 1954	58	240,028	420	1,288,665	478	1,528,693
1980						
Alabama	-	-	5	28,495	5	28,495
Alaska	-	-	96	495,680	96	495,680
California	4	18,915	138	741,770	142	760,685
Florida	-	-	35	201,600	35	201,600
Louisiana	933	4,029,519	478	2,127,361	1,411	6,156,880
Louisiana-Salt	2	4,995	-	-	2	4,995
Texas	186	970,805	147	794,841	333	1,765,646
Mid-Atlantic	-	-	126	737,304	126	737,304
South Atlantic	-	-	43	224,813	43	224,813
North Atlantic	-	-	63	358,659	63	358,659
TOTAL ACTIVITY DURING 1980	1,125	5,024,234	1,131	5,710,523	2,256	10,734,757

TABLE 1-2 WELL STATUS, OUTER CONTINENTAL SHELF, AS OF DECEMBER 31, 1979, AND DECEMBER 31, 1980 (USGS, 1981)

Year state	New wells drilling Active	New wells drilling Susp'd	Producible zone completions: Wells completed	Producible zone completions: Active Oil	Producible zone completions: Active Gas	Producible zone completions: Shut-in Oil	Producible zone completions: Shut-in Gas	Producible zone completions: Total active & shut-in	Total wells
1979									
Alaska	2	-	-	-	-	-	-	-	27
Atlantic	4	-	-	-	-	-	-	-	32
California	4	11	223	205	-	6	-	211	441
MAFLA[a]	5	10	50	47	4	7	1	59	183
Louisiana	114	382	8,169	3,175	2,653	1,018	638	7,484	14,970
Oregon	-	-	-	-	-	-	-	-	4
Texas	46	187	522	41	308	15	68	432	1,651
Washington	-	-	-	-	-	-	-	-	8
TOTAL	175	590	8,964	3,468	2,965	1,046	707	8,186	17,316
1980									
Alaska	-	-	-	-	-	-	-	-	21
Atlantic	2	-	-	-	-	-	-	-	32
California	10	37	246	213	-	14	-	227	531
MAFLA[a]	2	36	70	54	-	9	3	66	234
Louisiana	130	479	8,618	3,045	2,596	1,194	806	7,641	15,868
Oregon	-	-	-	-	-	-	-	-	8
Texas	47	187	704	81	399	27	112	619	1,927
Washington	-	-	-	-	-	-	-	-	4
TOTAL	191	739	9,638	3,393	2,995	1,244	921	8,553	18,625

[a] MAFLA = Mississippi, Alabama, Florida.

The Gulf of Mexico has been the location of the greatest past and present offshore oil and gas activity. Through 1981, 84 percent of all U.S. offshore oil and gas wells were in the Gulf of Mexico (NRC, 1983). Within the Gulf itself, the most successful area has been the Louisiana outer continental shelf. Offshore oil and gas wells in the Louisiana OCS area numbered approximately 19,200 through 1981, and constituted about 88 percent of all wells in the Gulf of Mexico (NRC, 1983).

Future domestic energy needs will continue to encourage development of offshore fossil fuel resources. An extensive effort to find and develop new reserves will be required, both on land and in old and new offshore drilling areas. Some new offshore fields currently considered for development are off southern California, Alaska, and new areas in the Gulf of Mexico (Mobile Bay), with some interest in the Atlantic. Regulatory agencies, the industry, and many citizens have been concerned about the potential environmental impact of discharges from offshore drilling platforms and production facilities.

Offshore oil and gas activities can be categorized into exploratory, developmental, and production operations. Exploratory drilling operations are conducted from drill barges, jack-up rigs, drilling ships, or semi-submersible rigs to identify the location of producing formations. Development operations are conducted on platforms from which multiple wells are drilled after a commercially exploitable reserve has been identified. Production operations ensue during and after developmental drilling. Oil and gas production may begin after drilling rigs have been removed; however, sometimes production is started on early wells while drilling continues on subsequent wells.

Modern drilling practices most commonly use a three-cone roller cutter bit, which is rotated against the bottom of the drill hole to grind through the rock. The bit is rotated by means of a high-strength steel pipe called the drill string, consisting of numerous 30-foot lengths of pipe threaded together. Drilling fluids are suspensions of solids, in either water or oil, circulated in the hole, which serve several purposes in the drilling operation. The most important of these are to maintain downhole pressure, lubricate and cool the drill bit, and remove drill cuttings to the surface. Drilling fluid passes down through the hollow drill string, out through the bit, and back up the space (annulus) between the drill string and the borehole wall. The basic drilling process and associated discharges are discussed below and shown in Figure 1-2.

During the first 50 m to 150 m (164 ft to 492 ft) of drilling, seawater is generally used as the drilling fluid; muds and cuttings (the drilled rock fragments) are discharged directly to the seafloor. Then the surface conductor pipe and blowout preventer are set and the marine riser is installed. From this point on, a specially formulated drilling fluid is added and continuously returned to the drilling rig, cleaned of cuttings, and recirculated to the hole.

Well depth varies from area to area and by type of well (Table 1-3, API 1983). In state waters, average well depths ranged from 2,080 m (6,345 ft) in California to 3,586 m (10,929

Figure 1-2 Discharges From The Drilling Operation

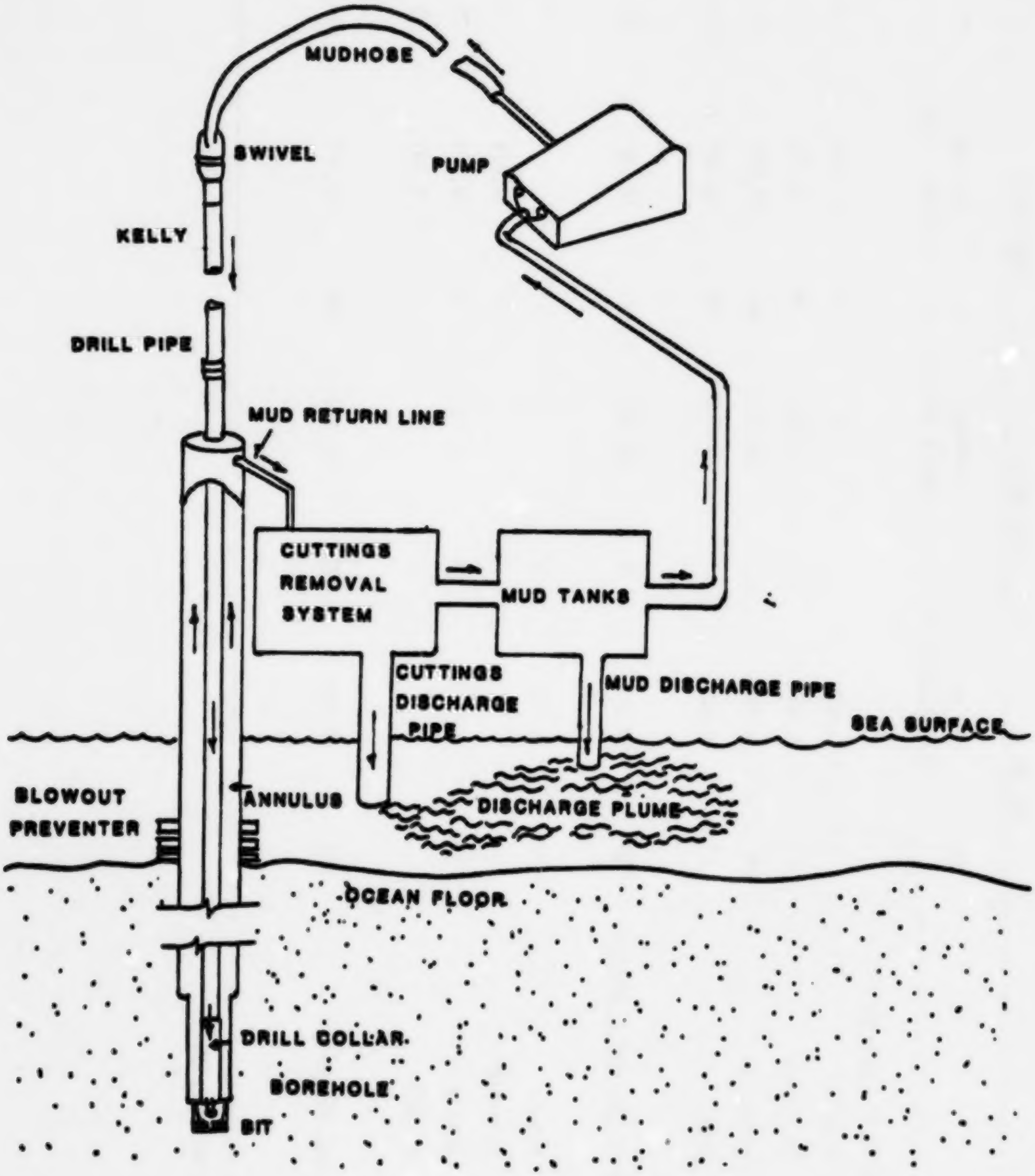

TABLE 1-3

NUMBER AND AVERAGE DEPTH OF OFFSHORE WELLS
COMPLETED IN 1982

	OIL WELLS		GAS WELLS		DRY WELLS		TOTAL	
	n	Average Depth (ft.)	n	Average Depth (ft.)	n	Average Depth (ft.)	n	Average Depth (ft.)
Wells in State Waters								
Alaska	1	10,400	-	-	2	11,194	3	10,929
California	153	5,804	5	12,102	16	9,718	174	6,345
Louisiana	280	9,997	277	10,837	343	10,830	900	10,573
Texas	17	8,827	137	9,350	146	10,088	300	9,678
Wells in Federal Waters	35	12,043	23	10,789	29	10,738	87	11,276
Alaska	2	13,262	-	-	-	-	2	13,262
Atlantic	-	-	-	-	-	17,036	5	17,036
Gulf North	33	11,970	23	10,789	19	10,420	75	11,215
Pacific	-	-	-	-	5	5,647	5	5,647
Total Offshore	486	8,784	442	10,388	536	10,390	1,464	9,930

From: API 1983.

ft) in Alaska. Average well depth in Louisiana was 3,223 m (10,573 ft). In Federal waters, average well depths ranged from 1,853 m (5,647 ft) in the Pacific to 5,589 m (17,036 ft) in the Atlantic.

Exploratory and development wells can have widely varying depths and frequencies, depending on the general location (Table 1-4). Although common statements are that exploratory wells are much deeper than development wells, this appears to be true only in offshore California waters: 1,553 m (5,096 ft) for development wells, and 2,918 m (9,574 ft) for exploratory wells. For all other areas, such distinctions are much less pronounced. In fact, for wells in federal waters in the Gulf of Mexico, the exploratory wells are actually shallower (3,024 m or 9,922 ft) than development wells (3,400 m or 11,156 ft). Exploratory wells average 3,155 m (10,351 ft) versus 2,749 m (9,019 ft) for development wells; all wells (both exploratory and development) have an average well depth of 2,865 m (9,401 ft).

The results for total offshore wells are, however, much determined by California well data. Eliminating California wells nearly entirely eliminates the gap as well: exploratory wells average 3,169 m (10,398 ft) versus 3,035 m (9,957 ft) for development wells. All wells, without California wells included, have an average depth of 3,078 m (10,097 ft). All data reported here use weighted averages calculated from total well footage data. The discrepancies in average number of wells and well depths reported here results from reporting discrepancies between two API sources; API (1983) and API (1982a-1).

TABLE 1-4 DEPTH OF EXPLORATORY AND DEVELOPMENT WELLS REPORTED COMPLETED IN 1982

	DEVELOPMENT WELLS		EXPLORATORY WELLS		TOTAL	
	n	Average Depth (ft.)	n	Average Depth (ft.)	n	Average Depth (ft.)
Wells in State Waters						
Alaska	1	12,492			1	12,492
California	153	5,096	18	9,574	171	5,567
Louisiana	492	10,029	160	10,697	652	10,193
Texas	116	9,307	117	10,136	233	9,723
TOTAL	762	8,932	295	10,406	1,057	9,343
Wells in Federal Waters						
Alaska						
Atlantic						
Gulf North	31	11,156	23	9,922	54	10,630
Pacific	0		1	4,000	1	4,000
TOTAL	31	11,150	24	9,675	55	10,510
Total Offshore	793	9,019	319	10,351	1,112	9,401

Based on API 1982 a-1.

1.3 WASTE DISCHARGES

Discharges from offshore oil and gas activities include:

- drilling fluid (or drilling mud)
- drill cuttings and associated wash water
- produced water (also referred to as brine, or formation water)
- deck drainage
- sanitary waste
- domestic wastes
- test fluids
- produced sand
- ballast water
- bilge water
- desalinization unit discharges
- cementing unit deck drainage and excess cement slurry
- blow-out preventer (BOP) fluid
- boiler blowdown
- fire protection system test water
- non-contact cooling water

Discharges from the first five categories have received the most attention from regulators and researchers. The first three categories are the primary contributors of potentially toxic pollutants from offshore oil and gas operations, and will be covered in greatest detail in this report. Drilling fluid ("mud"), drill cuttings, and produced water discharges also are most significant by virtue of their constituents and volumes. Drill cuttings are discharged continuously during drilling, and a small amount of drilling fluid normally adheres to these cuttings. Drilling fluid discharges occur at intervals: when water is added to control fluid viscosity, when well casing is cemented, when the fluid system is changed, and at the end of drilling.

Produced water, which is the brine brought up with the oil or gas from the geologic formation during the production phase, either can originate from the formation itself, or from water injected to increase production. The unseparated crude oil is brought to the surface and treated to remove this produced water. Most produced oil or gas is transported to shore via pipelines. Exceptions occur where oil is stored aboard the platform or in tankers used for transport to shore.

Produced water contains trace metals, hydrocarbons, and concentrated salts. The oil/water separation process may also involve the addition of chemicals to improve process efficiency and reduce equipment corrosion. These additives can include biocides, deflocculants, emulsion breakers, and other chemicals that may be found in the discharged produced water.

Deck drainage and sanitary waste discharges are less significant than drilling fluid and produced water effluents. Deck drainage consists of rain water or wash water that is usually captured in gutters and transported to a sump tank for oil separation prior to ocean discharge. Sanitary waste is normally discharged after treatment by a U. S. Coast Guard-approved marine sanitation device. These discharges are greatest during the drilling phase, when manpower requirements are highest. Cementing unit deck drainage discharges contain compounds present in casing cement.

The blow-out preventer (BOP) is a unit placed below the drilling apparatus to stop the uncontrolled release of formation fluids that can cause a blowout. The BOP unit must be tested periodically according to Minerals Management Service (MMS) operating orders. Hydraulic fluid is released to the environment during testing. Produced sand is sand contained in the produced fluids and occurs in some wells. The sand usually settles out in the oil/water separator and is discharged directly to the ocean. These and the other remaining categories of discharges are discussed in greater detail in Section 2.

2.0 SOURCES OF DISCHARGES TO THE MARINE ENVIRONMENT

This section discusses the major discharges to the marine environment from offshore oil and gas operations, including drilling fluid, drill cuttings and produced waters.

2.1 SUMMARY

Various sources of discharges occur during offshore oil and gas operations. Major sources include:

- drilling fluid ("drilling mud")
- drill cuttings
- produced water ("formation water")

In addition, a number of less important sources exist. Such sources include sanitary and domestic wastes, deck drainage, fire protection system test water, blow-out preventor fluid, cementing unit deck drainage and excess cement slurry, non-contact cooling water, ballast water, and bilge water. The discussion below focuses on the three major sources of discharges.

2.1.1 Drilling Fluids

Drilling fluids are suspensions of solids, primarily barite ($BaSO_4$) and clay, with various additives in fresh water or seawater, to which mineral or diesel oil are frequently added as lubricants or to free stuck drill string. Drilling fluids help to maintain downhole pressure, as well as to lubricate, cool, and clean the drill bit. Drilling fluid formulations are highly dependent on the site, formation, and well depth at which drilling occurs.

Some of the major components used in drilling fluids include: barite, bentonite or attapulgite clays, (ferro)chrome lignosulfonate, lignite, polyanionic cellulose, sodium hydroxide, sodium bicarbonate, potassium chloride, and diesel/mineral oil. Other additives that can be used include hundreds of proprietary formulations broadly classified as biocides, flocculants, deflocculants, surfactants, emulsifiers, shale control agents, filtrate reducers, oxygen/sulfide/calcium scavengers, and corrosion inhibitors.

Given the variability of drilling mud formulations, U.S. EPA Region II and the Offshore Operators Committee (OOC) developed the generic mud concept to avoid having to perform chemical and toxicological characterization of each drilling mud discharged. Eight distinct generic mud formulations were identified as operationally necessary and sufficient for drilling activities. Although discussed as a single mud, a specific generic mud does not have a fixed formulation, but rather a list of approved components and concentration ranges for each approved component. No additives were allowed that would significantly increase the toxicity of any generic mud.

The variability of these generic muds is also discussed in the toxicity section, which presents the large toxicity differences observed between different batches of the same "generic" mud. Neither mineral oil nor diesel oil is an approved component of any of the generic mud recipes. Nonetheless, since the initial formulation of generic muds, diesel oil has been subsequently identified by the industry as a necessary component in drilling fluids, at periodic usage levels approximately equal to several other bulk components.

Although non-generic muds are comprised of much the same basic components as generic muds, other additives may be used without any restriction other than the BPT effluent limitation of "no free oil." The use of numerous other additives in their drilling fluids even further increases the variability in their physiochemical characteristics, and thus their toxicity.

Due to the very nature of drilling fluids (i.e., generally a thick suspension), nonuniformity of samples imposes a large inherent variability. Almost all investigations report a variety of problems with material handling, mixing, sampling, and extraction. Thus, results for most parameters display a large statistical variability. In addition, a nonuniformity of analytical methodologies in various studies further increases the overall variability of the available data.

Recent chemical characterizations of generic muds with no added oil show them generally to have a high 5-day Biochemical Oxygen Demand. The high solids content muds have a very high Biochemical Oxygen Demand (BOD_5: 1,373 to 2,743 mg/kg); 20-day Ultimate Oxygen Demand, (UOD_{20}: 1,733 to 4,223 mg/kg); Total Organic Carbon (TOC: 3,040 to 15,000 mg/kg), and Chemical Oxygen Demand (COD: 8,000 to 41,200 mg/kg). The low solids content generic muds (mud numbers 004, 005, and 006) have far lower values for these characteristics, with BOD_5 levels from 9 to 216 mg/kg, UOD_{20} levels from 124 to 286 mg/kg, TOC levels from 100 to 1,220 mg/kg, and COD levels from 420 to 4,200 mg/kg.

COD appears to reflect most accurately total organic content, whereas TOC reflects free, i.e., nonsequestered, organic content. However, added mineral oil up to 10 percent did not produce a positive sheen test or a commensurate increase in TOC, BOD, or UOD. Added mineral oil did produce an added oil concentration-related increase in COD.

Levels of added mineral oil, in excess of 1 percent, decreased the BOD/UOD, compared to levels prior to oil addition. Similar results were observed for high-sulfur diesel oil. This indicates a toxic effect of the added oil on the organisms that are responsible for generating the oxygen demand measured in the BOD/UOD tests. Toxicity also is evident from the abnormal time-versus-BOD curves, as well as BOD/UOD and BOD/COD ratios. Thus, samples containing oil will have an artificially low BOD because of the toxicity of the oil on the organisms used to measure BOD or UOD. Nearly all generic muds, including those to which no lubricant was added, contain some oil and grease component (up to 1 percent, most probably derived from the lignite component). Therefore, all BOD values, including generic muds both with and without added oil, could be underestimated. Following dispersion upon release in the environment, however, this artificial depression of BOD will be reduced. Thus, environmental dispersion will result in a substantial increase in total expressed BOD, compared to that measured.

Oil and grease data were highly variable for hot rolled generic muds and did not correlate with either TOC, COD, or total added mineral oil up to 10 percent. No equivalent data are available for nongeneric muds; thus, a large proportion of oil in drilling mud appears sequestered on the barite and/or bentonite (attapulgite) clay for the hot rolled generic muds.

Available metal analyses of drilling fluids are of a highly variable nature due to nonuniformity of both sampling and analytical techniques. Data for generic muds appear to indicate fairly high levels of antimony (up to 4.0 ppm w/w dry weight), arsenic (up to 17.2 ppm), and chromium (up to 908 ppm). Mercury and cadmium levels were always less than 0.75 ppm (w/w dry weight). Addition of oil did not significantly alter the metal content of generic muds. Metal content of the nongeneric muds was significantly higher than that of the generic muds, especially for copper (23.4 to 3,448 ppm) and iron (0.70 to 7.63 percent). No antimony, arsenic, or mercury data were available for the nongeneric muds. Cadmium levels (dry weight) ranged up to 11.8 ppm and exceeded 2.0 ppm in six of 11 samples.

Except for n-dodecane (C-12 olefin) at levels less than 1 ppm (w/w wet weight), no organics were identified by a GC/MS analysis of priority pollutants fractions of generic muds. Addition of mineral oil resulted in added oil concentration-dependent detection of phenanthrene, dibenzofuran, diphenylamine, and biphenyl at total levels up to 30.2 mg/kg (wet weight). Other studies report the presence of alkylated naphthalenes and phenanthrenes at low levels and high levels of other hydrocarbons, primarily cycloalkanes, following the addition of five percent mineral oil. Addition of five percent high-sulfur diesel oil resulted in detection of high levels of alkylated benzenes, naphthalenes, and phenanthrenes, as well as large quantities of n-alkanes. Of these chemicals only benzene, naphthalene, and phenanthrene are priority pollutants.

Data on levels of organics in nongeneric mud are limited to levels of diesel oil (up to 0.94 percent or 9,400 mg/kg), aliphatics (up to 7,200 mg/liter), and aromatics (up to 1,600 mg/liter). More detailed information was not available.

Given that 1,464 offshore wells were drilled in 1982 with an average drilling time of generally less than 60 days, a median estimate is that offshore drilling would result in an average annual oxygen demand of 48,300 tons of BOD from drilling fluid and cuttings. This number is six times higher than the total BOD loading from all ocean dumped municipal sewage sludge, and 30 times the COD. More importantly, this oxygen demand is highly clustered: 900 of 1,464 offshore wells drilled in 1982 were in Louisiana state waters.

Oxygen demand and oil content are important factors in the toxicity of drilling fluids. However, the test phase and the analytical determination of "oil" (or "diesel equivalents") affect the correlation between oil content and toxicity. This topic is discussed further in Section 4.

2.1.2 Drill Cuttings

Drill cuttings are the fragments of rock brought up in the drilling fluid from the drilled formation. Cutting are removed from the fluid by passing through a series of screens or hydrocyclones that remove particulates. Generally, shale shakers remove particles larger than 440 μm, (fine screen, larger than 120 μm,); desanders remove particles in excess of 75 μm; and desilters remove particles in excess of 5 μm.

Recovered cuttings are discharged from the platform. Some amount of drilling fluid (approximately 5 percent, w/w) adheres to these particles.

Extremely limited published data on the actual composition of cuttings exist. In addition, composition will vary widely from formation to formation. Based on the only available data, for deep cuttings (>14,000 ft), cuttings appear much lighter than most drilling fluids with densities from 1.0 to 1.6 g/ml. Water content of cuttings discharges appear to be about 20 to 30 percent. BOD and UOD average approximately 8,000 and 20,000 mg/kg, extremely high compared to sewage sludges (500 to 3,000 mg/kg). TOC ranges from 23,000 to 51,000 mg/kg, and COD ranges from 90,000 to 270,000 mg/kg (or 9 to 27 percent). Cuttings from oil-based mud systems can have free oil, as evidenced by positive sheen tests at the 15 g level (i.e., one percent or less free oil), although oil and grease levels varied from one to 11 percent. Prior to washing, TOC, COD, sheen test results, and oil and grease data generally indicated higher levels, while lower BOD and UOD levels were observed prior to washing.

Metal levels, as expected, are highly variable. Mercury levels were less than 0.5 ppm (dry weight), whereas cadmium levels exceeded 2 ppm on two of three occasions. Levels of organics in cuttings were extremely high compared to generic drilling fluids with levels of polynuclear aromatics of up to 310 mg/kg, aromatic amines of up to 48 mg/kg, and with other base-neutral organics of up to 255 mg/kg. These findings probably are a result of contamination from the diesel oil mud system, although crude oil contamination from the producing zones of the formation cannot be eliminated as another source.

2.1.3 Produced Water

When oil and gas are produced, water is often produced along with them. This water is known as produced water, formation water, or brine. Produced water may originate from the reservoir or from waterflood treatment of the field, i.e., from injecting water into the formation to increase oil recovery. The quantity of produced water is dependent upon the method of recovery and the nature of the formation. Generally, the quantity increases with time for particular reservoirs. However, it can vary greatly among formations. Produced water discharges estimated for the EPA verification study ranged between 134 bbl/day and 150,000 bbl/day (21-23,835 m^3/day). Produced water from offshore operations may be discharged directly to the ocean from pipes either above or below the water surface. In some cases, the water is piped to shore for treatment and/or onshore injection; in other cases, the water may be reinjected offshore either for disposal or pressure maintenance purposes.

Produced water generally can be characterized as a brine having salinities that may exceed those of ambient seawater. Chloride levels of 37,000-110,000 ppm occurred in produced water for ten platforms off Louisiana; normal values for seawater are approximately 19,000 ppm. Produced water will contain petroleum hydrocarbons (especially lower molecular weight compounds) and metals, and may contain biocides and other additives.

Lower molecular weight hydrocarbons are more soluble in produced water than the higher molecular weight compounds. Among the lower molecular weight hydrocarbons are the volatile liquid hydrocarbons, which include the light aromatics (benzene through naphthalene). These are among the most immediately toxic components of petroleum. Concentrations on the order of 10-20 ppm have been measured in produced water for these chemicals. In the EPA's 30-platform study, naphthalene was found at concentrations on the order of 0.02-1.5 ppm. A number of related compounds (e.g., alkylated naphthalenes) are known to be present in produced water, but were not specifically analyzed in the platform verification study.

The concentrations of aromatics in produced water can be used, together with information on the volumes of discharges, to estimate discharge rates for specific chemicals. Discharge quantities for several chemicals that have been examined (benzene, toluene, and ethylbenzene) could exceed 10 kg/day for larger facilities (including central facilities). Ranges for average discharges (excluding central facilities), based on EPA's 30 platform study, yield the following discharge rates: benzene (<.01 to 7.7 kg/day), toluene (<.04 to 12.6 kg/day), and ethylbenzene (<.01 to 3.8 kg/day). Produced water also contains higher molecular weight alkanes and polynuclear aromatic hydrocarbons.

Inorganic compounds present in produced waters include heavy metals. Although various analyses have been carried out on heavy metals, several authors have noted there has been uncertainty about the quality of the data. Analyses conducted during EPA's 30-platform verification study indicated that the following metals were present in elevated concentrations (ranges in concentrations are shown in parentheses with zero identifying less than detection limits): Cd (0-98 ppb), Cu (0-1,455 ppb), Pb (0-5,700 ppb), Ni (0-276 ppb), Ag (0-107 ppb), and Zn (5-519 ppb). These ranges are similar to those reported in a previous EPA study. Other inorganic chemicals that may be present, and add to oxygen demand, include ammonia and hydrogen sulfide. For a project offshore southern California, the estimated concentrations of these two compounds could reach 800 mg/liter and 100 mg/liter, respectively.

Radioactive materials, such as radium, also have been found in some oil field produced waters. Ra-226 activities in filtered and unfiltered produced waters ranged from 16-395 pCi/liter, while Ra-228 activity ranged from 170 to 570 pCi/liter. These levels were significantly higher than background (open ocean surface waters normally contain 0.05 pCi/liter of radium). EPA's Office of Radiation Programs estimates resultant exposure at less than 1.0 mrem/yr, well below international guidelines.

Many different chemicals may be added during production operations and these may be present in the produced water discharge. These include biocides, coagulants, corrosion inhibitors, cleaners, dispersants, emulsion breakers, paraffin control agents, reverse emulsion breakers, and scale inhibitors. Detergents may also be found in produced water. The use of these chemicals varies from one platform to another.

Biocides may be used to control sulfate reducing bacteria, which may contribute in the corrosion of metal pipes and tanks. Biocides that have been used include K-31 (glutaraldehyde), KC-14 (alkyldimethylbenzyl chloride), acrolein, fatty amines, quaternary ammonium compounds, 2,2-dibromo-3-nitrilopropionamide, and chlorinated isothiazolines. A more complete list of biocides registered for use in both secondary recovery operations and drilling muds has been compiled by U.S. EPA.

One author has noted that most biocides are used in concentrations no higher than 20 ppm, and the concentrations in the effluents are usually a few ppm at most. Biocide application rates are usually in direct proportion to their efficacy. However, there is little quantitative data on concentrations of these chemicals in produced water discharges. This same author also noted that the biocide acrolein (which is usually scavenged and thus not detected in the effluent) may be reformed/released from its scavenged state following discharge, and was thought to be the agent responsible for eye and skin irritation of divers at the platform, at one point sufficient to force them out of the water.

Produced waters also may contain substances that exert an oxygen demand. One report on produced water estimated COD levels of 100-3,000 ppm (w/v) and BOD_5 levels of 300-2,000 ppm. The presence of oxygen consuming substances also has been evident in toxicity tests of produced water. For three- and eight-platform scenarios off Santa Barbara, annual BOD loadings were estimated at 6,740 and 18,000 metric tons. The authors contrasted these estimates with the combined total of 264,000 metric tons per year associated with five major municipal outfalls in southern California. They also also reported that there could be localized depressions of dissolved oxygen at the combined produced water discharge outfall. Using similar numbers to calculate the total BOD mass in produced waters released from Louisiana wells results in an estimated annual BOD release of 37,000 tons from produced water discharges.

2.2 DRILLING FLUIDS

Drilling fluid (or drilling "mud") is a suspension of solids and dissolved materials in water or oil, which serves several important functions in well drilling. Drilling mud helps lubricate and cool the drill bit, clean the bit, maintain sufficient hydrostatic pressure downhole, and remove drill cuttings from the hole to the surface. In the early days of oil drilling, water was used as the fluid. Today, wells are much deeper, drilling conditions more demanding, and drilling procedures far more sophisticated. Complex drilling fluids are necessary for efficient, economical, and safe completion of the well drilling operation. The types, functions, composition, and discharge of drilling fluids are examined in this section.

2.2.1 Types of Drilling Fluids

Drilling fluids may be water-based or oil-based. In water-based fluids, water forms the continuous phase of the mixture and may constitute 27 to 90 percent of the mud by volume. Either freshwater or seawater may be used.

Oil-based fluids are those in which oil, typically diesel oil, serves as the continuous phase and water as the dispersed phase. The most common kinds of oil-based muds in use today are invert emulsions in which water may constitute as much as 50 percent of the mud by volume. Other types of oil-based muds differ from invert emulsions in the amount of water used, method of controlling viscosity and thixotropic properties, wall-building materials, and fluid loss (Wright and Dudley, 1982). Oil-based muds are more expensive and more toxic than water-based muds, and would normally be used only for particularly demanding drilling conditions for which water-based fluids would prove inadequate.

There is currently an increased interest in the use of mineral oil-based muds as a substitute for diesel oil-based muds. While both muds possess the same desirable properties, mineral oil-based muds have a lower aromatic hydrocarbon content and are less toxic. Moreover, the mineral oil-based muds are not irritating to the skin and do not have a noxious odor (Petrazzuolo, 1983). Air, gas, mist, or foam may also serve as the drilling fluid in special situations, but these are not used offshore.

Water-based drilling fluids are the type most commonly used offshore. The Best Practicable Technology (BPT) effluent limitation stipulates no discharge of free oil for drilling muds and cuttings, and this has prevented the discharge of diesel oil- and mineral oil-based muds on the outer continental shelf. The cuttings in both cases are usually discharged after treatment. However, this varies depending on the requirements in National Pollutant Discharge and Elimination System (NPDES) permits issued by the regions or states. Mineral oil-based muds are not widely used, but their use is becoming more prevalent because they are less toxic than diesel oil-based muds.

In 1978 the U.S. Environmental Protection Agency (EPA) Region II granted offshore drilling NPDES permits to operators drilling on leases in the Baltimore Canyon. As a permit condition, the operators were required to perform a jointly funded drilling mud bioassay program.

The result was the development of the generic or standard mud concept by the Offshore Operators Committee with EPA Region II, in order to provide EPA with control over mud components and discharges without requiring that each operator perform bioassays and chemical test for each discharged mud.

Previously, EPA had not recognized differences in water-based mud systems and had classified all muds as either oil-based or water-based. However, for this joint industry program, the Offshore Operators Committee Task Force on Environmental Science and EPA Region II developed a spectrum of eight generic mud types that included essentially all water-based compositions and an acceptable drilling mud bioassay procedure.

These eight generic muds were identified by reviewing permit requests and selecting the minimum number of mud systems that would include all those mud types named by prospective permittees; these mud systems included virtually all water-based muds used on the OCS. Concentration ranges were specified for mud components to allow the operators sufficient flexibility to drill safely. Table 2-1 shows the formulations for each of the muds. Note that a high degree of variability is allowed in the formulation of each mud. Thus, two samples of the same generic mud will not necessarily have the same physical or chemical characteristics, nor the same toxicity.

In the eight generic mud systems, only major components were specified. Specialty additives (e.g., lost circulation materials, lubricity agents, etc.) needed for special drilling situations were not included. If an unexpected need for a

TABLE 2-1 EPA GENERIC DRILLING MUD TYPES
(Cole and Mitchell, 1984)

1. Seawater/Potassium/Polymer Mud

Components	#/BBL[a]
KCl	5-50
Starch	2-12
Cellulose Polymer	0.25-5
XC Polymer	0.25-2
Drilled Solids	20-100
Caustic	0.5-3
Barite	0-450
Seawater	As Needed

2. Seawater/Lignosulfonate Mud

Components	#/BBL
Attapulgite or Bentonite	10-50
Lignosulfonate	2-15
Lignite	1-10
Caustic	1-5
Barite	25-450
Drilled Solids	20-100
Soda Ash/Sodium Bicarbonate	0-2
Cellulose Polymer	0.25-5
Seawater	As Needed

3. Lime Mud

Components	#/BBL
Lime	2-20
Bentonite	10-50
Lignosulfonate	2-15
Lignite	0-10
Barite	25-180
Caustic	1-5
Drilled Solids	20-100
Soda Ash/Sodium Bicarbonate	0-2
Freshwater	As Needed

4. Nondispersed Mud

Components	#/BBL
Bentonite	5-15
Acrylic Polymer	0.5-2
Barite	25-180
Drilled Solids	20-70
Freshwater	As Needed

TABLE 2-1 EPA GENERIC DRILLING MUD TYPES
(Cole and Mitchell, 1984)

(Continued)

5. Spud Mud (slugged intermittently with seawater)

Components	#/BBL[a]
Attapulgite or Bentonite	10-50
Lime	0.5-1
Soda Ash/Sodium Bicarbonate	0-2
Caustic	0-2
Barite	0-50
Seawater	As Needed

6. Seawater/Freshwater Gel Mud

Components	#/BBL
Attapulgite or Bentonite Clay	10-50
Caustic	0.5-3
Cellulose Polymer	0-2
Drilled Solids	20-100
Barite	0-50
Soda Ash/Sodium Bicarbonate	0-2
Lime	0-2
Seawater/Freshwater	As Needed

7. Lightly Treated Lignosulfonate Freshwater/Seawater Mud

Components	#/BBL
Bentonite	10-50
Barite	0-180
Caustic	1-3
Lignosulfonate	2-6
Lignite	0-4
Cellulose Polymer	0-2
Drilled Solids	20-100
Soda Ash/Sodium Bicarbonate	0-2
Lime	0-2
Seawater to Freshwater Ratio	1:1 approx.

TABLE 2-1 EPA GENERIC DRILLING MUD TYPES
(Cole and Mitchell, 1984)

(Continued)

8. Lignosulfonate Freshwater Mud

Components	#/BBL[a]
Bentonite	10-50
Barite	0-450
Caustic	2-5
Lignosulfonate	4-15
Lignite	2-10
Drilled Solids	20-100
Cellulose Polymer	0-2
Soda Ash/Sodium Bicarbonate	0-2
Lime	0-2
Freshwater	As Needed

[a] (pounds per barrel)

specialty additive arose, the operator was required to submit the chemical composition, usage rates, and toxicity data on the additive to EPA prior to its discharge.

Based on this information, the EPA Region would either approve or disapprove the discharge of mud containing the additive on a case-by-case basis. If there was a continuing need for the additive, the operator could then submit bioassay data on the mud containing the additive. The discharge would only be allowed if the additive did not increase mud toxicity unacceptably. Once an additive became "approved" in this way, future discharges of muds containing the additive would be allowed without conducting additional bioassays.

The approach has proved to be practical, and the generic mud concept subsequently has been incorporated into individual and general permits issued by EPA coastal Regions that have or intend to issue NPDES permits to offshore facilities.

2.2.2 Functions of Drilling Fluids

Drilling fluids are specifically formulated to meet the physical and chemical conditions of each particular well site. Seawater alone is normally used to drill the first 50 to 100 m (164 to 328 ft) of the well, and the drill cuttings produced are discharged directly at the sea floor. After this point, casing is set, and a specially formulated drilling mud will be used. Mud composition is affected by geographic location, well depth, and the rock type through which drilling will occur, and will be altered as depth increases and rock formations and other conditions change. The primary functions of drilling fluids are:

- maintaining sufficient hydrostatic pressure to prevent influx of formation fluids into the well-bore
- cooling and lubricating the drill bit and drill string
- removing cuttings and transporting them to the surface
- maintaining cuttings in suspension during interruptions in drilling
- coating the bore wall with an impermeable filter cake to prevent fluid loss to permeable formations
- minimizing corrosion
- maximizing the drilling rate

2.2.3 Components of Drilling Fluids

Four kinds of materials represent about 90 percent of the total tonnage of all additives used in drilling mud--barite, clays, lignosulfonates, and lignites. Other major components include caustic soda, soda ash, lost circulation materials, and other specialty additives as dictated by well requirements. The functions of some common drilling fluid additives are described below and in Table 2-2.

2.2.3.1 Barite

Barite is the mineral most commonly used as a weighting material in drilling mud. Barite is mostly barium sulfate, which is 59 percent barium by weight. Barite is a naturally occurring mineral, is readily available and inexpensive, and is characterized by high specific gravity (4.1 to 4.3 g/ml), low water solubility (0.03 ppm in seawater), low Mohs' hardness (2.5-3.5), and chemical inertness.

TABLE 2-2 FUNCTIONS OF SOME COMMON DRILLING FLUID CHEMICAL ADDITIVES

1. Alkalinity and pH Control: Caustic soda, sodium carbonate, sodium bicarbonate, and lime are commonly used to control the pH of drilling fluid and secondarily to control bacterial growth.

2. Biocides: Paraformaldehyde, alkylamines, caustic soda, lime, and starch preservatives are typically used as bactericides to reduce the bacteria count in the mud system. Halogenated phenol bactericides are no longer permitted for OCS use.

3. Calcium Removers: Caustic soda, soda ash, sodium bicarbonate, and certain polyphosphates are added to control the calcium buildup which can prevent the proper functioning of drilling equipment.

4. Corrosion Inhibitors: Hydrated lime and amine salts are added to drilling fluids to reduce corrosion potential.

5. Defoamers: Aluminum stearate and sodium aryl sulfonate are commonly used to reduce foaming action that occurs particularly in brackish waters and saturated saltwater muds.

6. Emulsifiers: Ethyl hexanol, silicone compounds, modified lignosulfonates, and amionic and nonionic products are used as emulsifiers to create a homogeneous mixture of two liquids.

7. Filtrate Loss Reducers: Bentonite clays, cellulose polymers such as sodium carboxymethyl cellulose (CMC) and hydroxyethyl cellulose (HEC), and pregelated starch are added to drilling fluid to prevent the invasion of the liquid phase into the formation.

8. Flocculants: Salt (or brine), hydrated lime, gypsum, and sodium tetraphosphate cause suspended colloids to group into "flocs" and settle out.

9. Foaming Agents: These products are designed to foam in the presence of water and allow air or gas drilling through formations producing water.

10. Lost Circulation Materials: Wood chips or fibers, mica, sawdust, leather, nut shells, cellophane, shredded rubber, fibrous mineral wool, and perlite are all used to plug pores in the well-bore wall to reduce or stop fluid loss into the formation.

11. Lubricants: Certain hydrocarbons, mineral and vegetable oils, graphite powder, and soaps are used as lubricants to reduce friction between the drill bit and the formation.

12. Shale Control Inhibitors: Gypsum, sodium silicate, polymers, limes, potassium chloride, and salt reduce wall collapse caused by swelling or hydrous disintegration of shales.

13. Surface Active Agents (Surfactants): Emulsifiers, de-emulsifiers, and flocculants are used to alter a fluid's viscosity, or vary its gel strength.

TABLE 2-2 FUNCTIONS OF SOME COMMON DRILLING MUD CHEMICAL ADDITIVES
(Continued)

14. Thinners: Lignosulfonates, tannins, and various polyphosphates are used as thinners. These additives disperse solids by deflocculating associated clay particles.

15. Weighting Materials: Products with high specific gravities, predominantly barite, calcium carbonate, siderite, and iron oxides (hematite), are used to increase drilling mud weight.

16. Petroleum Hydrocarbons: These products (often diesel oil) may be added to mud systems for specialized purposes such as freeing a stuck pipe. Hydraulic testing of blowout preventers also requires the use of hydrocarbons

Trace impurities in barite include arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, and zinc. These impurities may occur as substitute metals in the barium sulfate structure or as insoluble sulfides. The sulfides most often associated with barite deposits are sphalerite (ZnS), galena (PbS), and pyrite (FeS_2) (Kramer et al., 1980; Macdonald, 1982). Kramer et al., (1980) showed that sphalerite in barite deposits concentrates mercury and cadmium and pyrite concentrates arsenic. Veined deposits of barite may show concentrations of lead, zinc, mercury, and cadmium of one to two orders of magnitude above background; bedded deposits may show only minor enrichment relative to background.

Analyses of four separate samples of barite, (1) API Standard, (2) North American, (3) European, (4) North American revealed wide variations in trace metal content (CENTEC, 1984, Table 2-3). The highest variability was observed for mercury, arsenic, and iron. Whereas the European barite contained 1.78 ppm mercury, the API standard contained 0.035 ppm, and both North American samples contained less than the detection level of 0.030 ppm. Arsenic levels in the API standard were 8.40 and 9.30 ppm (see Table 2-3) as compared to less than detection (0.200 ppm) or 0.357 ppm for the other three barite samples. This latter anomaly may be associated with the iron anomaly, since arsenic is often found in association with sulfurous ores such as FeS_2. Iron levels in the API standard barite were 25,600 ppm as compared to 128 to 241 ppm for the other three samples.

Similar but less pronounced anomalies in the API standard were observed for copper and aluminum levels. Lead and antimony levels appeared much higher in the API and European

TABLE 2-3 METAL CONCENTRATIONS IN BARITE SAMPLES[a]

	METHOD			API Standard Barite #1[b]	N. American Barite #2[b]	European Barite #3[b]	N. American Barite #4[b]
Al	FLAME	API	MG/KG	524	72.6	926	55.0
Ba	FLAME	API	MG/KG	304	1250	642	834.0
Be	FLAME	API	MG/KG	<1.20	<1.20	<1.20	<1.20
Cd	FLAME	API	MG/KG	<1.20	<1.20	<1.20	<1.20
Cr	FLAME	API	MG/KG	<3.00	<3.00	<3.00	<3.00
Cu	FLAME	API	MG/KG	68.4	5.72	12.0	2.55
Fe	FLAME	API	MG/KG	25600	128	241	190
Ni	FLAME	API	MG/KG	<3.00	<3.00	<3.00	<3.00
Pb	FLAME	API	MG/KG	45.4	<6.00	23.8	<6.00
Zn	FLAME	API	MG/KG	164	7.69	202	6.04
Hg	NOS	NOS	MG/KG[a]	0.035(1)	<0.030	1.78	<0.030
Ag	FURNACE	EPA	MG/KG[a]	6.34	<0.200	1.40	0.619[a]
		API	MG/KG[a]	1.84(1)[c]	–[c]	2.39(1)[c]	1.88
As	FURNACE	EPA	MG/KG[a]	8.40	<0.200	<0.200	<0.200
		API	MG/KG[a]	9.30	0.357	<0.200	<0.200
Se	FURNACE	EPA	MG/KG[a]	<0.500	<0.500	<0.500	<0.500
		API	MG/KG[a]	–[c]	–[c]	–[c]	–[c]
Sb	FURNACE	EPA	MG/KG[a]	1.40	<0.200	3.06	<0.200
		API	MG/KG[a]	1.06	0.090(1)	2.69	1.18
Tl	FURNACE	EPA	MG/KG[a]	<0.200	<0.200	<0.200	<0.200
		API	MG/KG[a]	<0.200	<0.200	<0.200	0.286

FROM CENTEC, 1984

[a] Wet weight basis.
[b] Mean of duplicate analysis.
[c] Furnace could not be run for Se or Hg using API method of sample digestion.
(1) Single analysis only.

NOS = Not otherwise specified.

barite as compared to the two North American barites. It should be noted here that the API barite standard is formulated based on physical not chemical characteristics.

Barite and its associated contaminant metals are of low solubility in seawater, and will remain primarily in particulate form after discharge. The solubility of the metals increases in sulfidic or reducing aquatic environments (Macdonald, 1982).

2.2.3.2 Clays

Bentonite is the most widely used clay in drilling fluids. Its crystal structure causes it to swell upon contact with water, and this gelling property suspends solid material and aids in the removal of drill cuttings from the borehole. The sealing properties of bentonite also enable it to form an impermeable filter cake on the well-bore wall to reduce loss of drilling fluid to the formation. When concentrated brine is encountered downhole, however, the swelling qualities of bentonite clays are severely reduced, and attapulgite or sepiolite clays are often substituted.

2.2.3.3 Lignosulfonates

Lignosulfonates are considered the best all-purpose deflocculants for thinning water-based drilling fluids, and serve to maintain the mud in a fluid state. Lignosulfonates also serve secondary functions as shale control agents. Deflocculants, rather than water, are usually used to thin barite-containing muds, because adding water would increase the total fluid volume, reducing barite concentration, and thus increasing the amount of barite necessary to achieve the proper density.

Ferrochrome lignosulfonate is a widely used form of lignosulfonate. It performs over a wide alkaline pH range, is resistant to common mud contaminants, is temperature stable to approximately 177° (350°), and will function in high soluble salt concentrations. Chromium can represent up to three percent of ferrochrome lignosulfonate by weight. Most of this chromium is in the trivalent form (as opposed to the more toxic hexavalent form), and is bound to clay particles, further limiting its bioavailability and toxicity (McCulloch et al., 1980). Chrome lignosulfonate is also commonly used in drilling muds.

2.2.3.4 Lignites

Lignites act as mud thinners and shale control agents, but they are less soluble in seawater than lignosulfonates. Lignite products are used to thin freshwater muds, reduce drilling fluid loss to the formation, and aid in the control of mud gelation at elevated temperatures. Lignites are manufactured in a variety of forms, such as chrome lignite.

2.2.3.5 Biocides

Biocides are added for control of bacterial growth to the following systems during drilling operations:

- water disposal systems (including wastewater treatment)
- waterflooding operations
- cooling water circulation systems
- drilling fluid/mud circulation systems

A recent EPA review (Zimmerman and deNagy, 1984) identified 27 chemicals as biocides used in both drilling muds and secondary recovery operations. Only one of 27 is a priority pollutant: pentachlorophenol, use of which is forbidden in any operation activity (FR 7/3/79). Recommended dosages are very situation-dependent and can vary from 1.0 to as high as 1200 ppm. Biocides with the lowest efficacy had the highest recommended dosage and vice versa. It should be noted here that not all wells will require use of biocides during development.

Toxicity data is available for the most prevalent biocides and is reviewed in Zimmerman and deNagy (1984). All of the recommended treatment levels appear high in comparison to acute and chronic effect levels for marine organisms.

2.2.3.6 Other Basic Additives

Other basic drilling fluid components include lime, caustic soda, sodium carbonate (soda ash), and sodium bicarbonate, which are used, among other functions, to control pH. The pH of drilling fluid typically ranges from 9.0 to 10.5 and is important because it affects the dispersibility of clays, solubility of various chemicals, corrosion of steel materials, and drilling fluid viscosity. Other such components function as shale control inhibitors, corrosion inhibitors, lubricants, and calcium removers. Usage of these additives varies widely but is generally less than 50 tons per well.

2.2.3.7 Specialty Additives

Specialty additives, in addition to biocides, include defoamers (to aid accurate determination of mud pit levels), surfactants and lubricants (to free a stuck drill string), filtrate reducers and lost circulation materials (to render the well-bore wall less permeable to fluid loss), and corrosion inhibitors. Specialty additive usage in the Gulf of Mexico typically constituted five to ten percent by weight of total mud component use (Cole and Mitchell, 1984). However, the specific geologic strata being drilled and well depth dictate additive needs. Deeper wells generally present more demanding drilling conditions, which in turn dictate the need for greater quantities of specialty additives. Table 2-4 gives examples of situations requiring special drilling fluid additives or formulations.

Although specialty additives are used in relatively small quantities, some of them may disproportionately contribute to the toxic effects of whole drilling fluids because of their high toxicity. The same holds true for process contaminants of drilling fluid discharges. For example, drill pipe dope and drill collar dope are applied to the threads of the drill pipe and drill collar to lubricate and seal the connection. Drill pipe dope is composed of 15 percent copper and 79 percent lead, while drill collar dope is 35 percent zinc, 20 percent lead, and 7 percent copper. These compounds may be the major source of the lead and one source of the zinc and copper found in drilling fluids (Shell Oil Co., 1978a, as in Petrazzuolo, 1981; and Ayers et al., 1980a). Toxicity is discussed in greater detail in Section 4 of this report.

2-4. SITUATIONS REQUIRING SPECIAL DRILLING FLUID ADDITIVES OR FORMULATIONS (PES, 1980)

Situation	Problems encountered	Control measures and/or additives
Shale formations	Water-based fluid may react with shale to cause swelling, binding of the drill string, fluid entry along fracture lines, sloughing, hole enlargement, or hole closure.	Shale control inhibitor additives such as gypsum, limes, polymers, lignosulfonates, and sodium silicates (see Table 2-2).
Lost circulation	Loss of whole drilling fluid to formations resulting when total pressure against formation exceeds total pressure of the formation. Low pressure formations include those which are: cavernous or open-fissure type; very coarse or permeable (such as loose gravel); easily fractured; and characterized by natural or intrinsic fractures.	Reduction of mud weight; adoption of special drilling methods such as "blind drilling," drilling under pressure, or drilling with air or aerated muds; placement of soft plugs using lost circulation materials (see Table 2-2); and use of thickening or cementing materials.
Excessive filtration or water loss	Excessive water loss to permeable formations may result in: thickening of the filter cake causing tight places in the hole and sticking of the drill string; sloughing or caving-in of shales; difficulties in interpreting electric logs used to identify geologic strata. Common contaminants such as salt, cement and anhydrite may cause flocculation of clays to the extent that they are no longer effective in controlling filtration or water loss.	Water loss may be reduced by adding bentonites, starch, CMC, polymers, and other filtrate loss reducers identified in Table 2-2.
Formation pressure control	Formation fluid pressure may be classified as abnormally high, normal, and subnormal. Subnormal pressure zones are subject to lost circulation problems. Normal and abnormally high pressure zones are subject to blow-out conditions.	Adjust drilling fluid to control formation pressure by increasing or decreasing amount of weighting materials (Table 2-2) used; alter the gel strength or viscosity of the mud by using surfactant additives (Table 2-2); and install blow-out prevention equipment.

TABLE 2-4. SITUATIONS REQUIRING SPECIAL DRILLING FLUID ADDITIVES OR FORMULATIONS (PES, 1980)
(Continued)

High bottom-hole temperatures	Elevated temperatures may cause mud components to react with each other with results such as accelerated thickening of fluids. Some additives and dispersants break down at high temperatures. Temperature-induced changes in mud properties may cause increased breakdown of formation leading to lost circulation, sloughing, etc.	Temperatures are a function of geologic age and formation and cannot be controlled. However, knowledge of borehole temperature (from geothermal gradient records or electric logs from adjacent wells) will allow selection of heat tolerant additives (e.g., chrome lignosulfonate muds are stable at temperatures up to 177°C [350°F]).

2.2.4 Chemical Characterization of Drilling Fluid

A recent EPA sponsored study (CENTEC, 1984) described the physicochemical characteristics of eight generic drilling fluids ("muds") as well as two muds (002/008) admixed with 1, 5, or 10 percent mineral oil. Table 2-1 shows the formulation used for these eight generic muds. These muds were the same as used in toxicity testing (see Section 4 and Duke and Parrish, 1984). Table 2-5 describes the physicochemical characteristics of these muds.

2.2.4.1 Conventional Parameters

For all generic muds the pH was between 8 and 10 with only the lime mud (003) having a pH of 12. [Admixing with oil resulted in highly variable changes in pH, most of which appear due to non-representative sampling/mixing.] Density varied between 1.44 and 2.15 except for two very light (thin) muds, 005 and 006, which had a density of 1.09 and also had the highest water content. Water content varied from 26.6 to 90.1 percent, with the heaviest mud having the least water content and vice versa.

Two biochemical oxygen demand parameters were characterized in several ways: Biochemical Oxygen Demand (5 day: BOD_5) and Ultimate Oxygen Demand (20 day: UOD_{20}). Both were performed with CENTEC activated seed and Polyseed in artificial seawater. Average BOD_5 varied from 9 to 2,743 mg/kg with muds 004, 005, and 006 having very low BODs (9 to 216 mg/kg) and the other muds having BOD_5's ranging from 1,373 to 2,743 mg/kg. UODs showed a similar trend with values ranging from 124 to 4,223 mg/kg. Again, two disparate groups were

TABLE 2-5

CONVENTIONAL WATER QUALITY PARAMETERS OF GENERIC DRILLING FLUIDS

Generic Mud	Type of Mud	pH	Density	% Weight Loss (103°C) (a)	BOD-5 SOW CENTEC (ACT) mg/kg(b)	BOD-5 SOW POLY-SEED mg/kg mg/kg(b)	UOD-20 SOW + CAS mg/kg(b)	UOD-20 SOW + POLY mg/kg(b)	TOC mg/kg(c)	COD mg/kg(b)	SHEEN TEST (15g)(b)	Oil and Grease mg/kg Sonification(b)	Oil and Grease mg/kg Soxhlet Extraction(a)
001	KCL Polymer Mud	8.05	1.74	34.1	1813	2037	4223	3407	3,040	8,000	0/3	532	4,860
002	Seawater Lignosulfonate Mud	10.10	2.15	26.6	1483	1373	2717	2330	15,000	39,900	0/3	1,270	2,750
003	Lime Mud	11.92	1.73	44.0	1657	2743	3207	3963	15,000	41,200	0/3	796	1,240
004	Non-dispersed Mud	8.60	1.44	659.6	< 50	10	136	286	1,220	4,200	0/3	520	1,820
005	Spud Mud	8.10	1.09	90.1	< 50	9	160	124	100	420	0/3	597	140
006	Seawater/Freshwater Gel Mud	7.95	1.09	88.0	181	216	130	285	686	1,800	0/3	661	672
007	Lightly treated Lignosulfonate Mud	8.50	1.44	56.2	1470	1386	2187	1733	5,650	15,300	0/3	1,710	572
008	Lignosulfonate Freshwater Mud	8.60	2.12	27.1	1530	1393	2413	1980	14,200	34,900	0/3	1,400	7,380
002-00	Mud 002	10.10	2.15	26.6	1483	1373	2717	2330	15,000	39,900	0/3	1,270	2,750
002-01	Mud 002 + 1% Mineral Oil	10.95	2.15	26.4	1416	2223	4073	5803	15,900	46,100	0/3	2,730	2,400
002-05	Mud 002 + 5% Mineral Oil	9.75	2.07	27.2	3416	2157	8340	7473	26,300	98,300	0/3	11,700	23,400
002-10	Mud 002 + 10% Mineral Oil	8.55	2.04	25.7	1558	1877	9273	6190	36,500	144,000	0/3	14,800	40,400
008-00	Mud 008	8.60	2.12	27.1	1530	1393	2413	1980	14,200	34,900	0/3	1,400	7,380
008-01	Mud 008 + 1% Mineral Oil	8.00	2.21	27.0	1373	2383	4423	4297	13,400	53,800	0/3	1,990	2,560
008-05	Mud 008 + 5% Mineral Oil	9.22	2.23	26.3	2207	2023	9773	6940	20,800	75,300	0/3	7,080	7,670
008-10	Mud 008 + 10% Mineral Oil	8.50	2.25	25.6	1423	1633	7863	6497	24,200	99,600	0/3	12,300	2,800

FROM: CENTEC, 1984 ALL DATA WET WEIGHT

(a) Average of duplicates.
(b) Average of triplicate.
(c) Average of three triplicates.

apparent: Muds 004, 005, and 006 had UODs ranging from 124 to 286 mg/kg, whereas the remaining muds had UODs from 1,733 to 4,223 mg/kg. UOD_{20}'s were approximately 1.5 to 2 times higher than BODs with the exception of muds 004 and 005 where UODs were from 3 to 28 times higher (which may be an artifact as a result of the low values) and mud 006 where UOD was lower than the BOD for the CENTEC activated seed, which appears to be an aberration when compared to the results for 004 and 005. Total organic carbon (TOC) content was lowest (100 to 1,220 mg/kg) in muds 004, 005, and 006, intermediate (3,040 to 5,650 mg/kg) in muds 001 and 007 and highest in muds 002, 003, and 008 (14,200 to 15,000 mg/kg). Chemical Oxygen Demand (COD) was approximately 2.5 to 3 fold higher than TOC values but followed the same trend. COD values were lowest for mud 004, 005, and 006 (420 to 4,000 mg/kg) intermediate for muds 001 and 007 (8,000 to 15,300 mg/kg), and highest in muds in 002, 003, and 008 (34,900 to 41,200 mg/kg).

None of the generic muds produced a sheen test at levels of 15 grams mud added, which should correspond to levels of free oil of less than one percent. Oil and grease levels were indeed low: between 520 and 1,710 mg/kg after sonification and between 140 and 7,300 mg/kg after Soxhlet extraction. The oil and grease values did not show any logical correspondence to TOC/COD values. Oil and grease (sonification) was highest in 002, 007, and 008 (1,270-1,710 mg/kg), and intermediate (520 to 796 mg/kg) in all other muds. Oil and grease (soxhlet) was highest in 001, 002 and 008 (2,750 to 7,380 mg/kg) intermediate in 003 and 004 (1,240 and 1,820 mg/kg) and lowest in 005, 006, and 007 (140 to 672 mg/kg). Oil content data based on retort method did not present reliable information.

Admixture of mineral oil into muds 002 and 008 at levels of 1, 5, and 10 percent (samples 002-01, 002-05, 002-10, and 008-01, 008-05, 008-10, respectively) resulted in some rather inconsistent results. Both muds are heavy and thus admixture of lighter oil should result in lower density and lower water content. Although density for the 002 series decreased, density for the 008 series increased with oil addition. Similarly, pH went down for the 002 series with inconsistent results for the 008 series.

One would expect a continuous increase in oxygen demand upon addition of oil. This, however, is not the case. Indeed, addition of 1 percent oil results in an increase of biochemical oxygen demand. Toxicity (as indicated by decreased BOD/UOD), however, occurs at the 5 or 10 percent level. Note also that addition of 1 to 10 percent oil (or 990 to 90,909 mg/kg) does not result in commensurate increase in biochemical oxygen demand nor (Table 2-5) in total organic carbon or oil and grease levels. Chemical oxygen demand, on the other hand, appears to reflect added oil levels well: very well for mud 002, not nearly as consistent for mud 008. Surprising are the sheen test results: although designed to detect free oil levels of 1 to 10 percent, not even the samples with at least 10 percent added mineral oil tested positive.

These results are not easily explainable: the added mineral oil appears present based on COD data. However, neither TOC, oil and grease (soxhlet or sonification), the sheen test, nor the BOD/UOD result is indicative of the known amount of oil added. The BOD/UOD results are probably a result of oil toxicity to the organisms. The other results reflect two things: nonrepresentative sampling and a nonavailability of the oil, possibly as the result of the formation of gels. Given the boiling point of mineral oil, it appears unlikely that mineral oil evaporated from this solution during sample preparation.

2.2.4.2 Metals

CENTEC (1984) reported metal analysis by atomic absorption spectrometry for the following metals: aluminum, antimony, arsenic, barium, beryllium, cadmium, copper, chromium, iron, lead, mercury, nickel, selenium, silver, thallium, and zinc (See Table 2-6). Beryllium, nickel, and selenium levels were all below detection levels of 1, 6, and 3 ppm, respectively. With few exceptions no remarkable excursions in metal levels could be observed. Addition of mineral oil did not affect metal levels. Barium data reported were highly variable and unreliable due to incomplete (weak acid) sample digestion.

Chrome levels were highest (≥ 300 ppm) in muds 002, 003, 007, and 008 and nondetectable (<3 ppm) in all other muds. Arsenic levels were highest (11.7-17.2 ppm) in muds 003 and 008, intermediate (2.40-5.25 ppm) in muds 001, 002, and 004, and lowest (≤ 0.6 ppm) in muds 005, 006, and 007. Antimony levels were highest (4 ppm) in mud 001, intermediate (0.26 to 1.06 ppm) in muds 002, 003, 004, and 008, and nondetectable (<0.06 ppm) in muds 005, 006, and 007. Mercury levels were highest in mud 003 (0.753 ppm), intermediate (0.261-0.437 ppm) in muds 001, 002, 004, 006, and 008, and lowest (<0.1 ppm) in muds 005 and 007. Cadmium levels were less than 0.75 ppm in all muds.

TABLE 2-6 METAL CONCENTRATIONS IN GENERIC DRILLING FLUIDS

Generic Mud	Type of Mud	Zn mg/kg FLAME(a)	Be mg/kg FLAME(a)	Al mg/kg FLAME(a)	Ba mg/kg FLAME	Fe mg/kg FLAME(a)	Cd mg/kg FLAME(a)	Cr mg/kg FLAME(a)	Cu mg/kg FLAME(a)	Ni mg/kg FLAME(a)	Pb mg/kg FLAME(a)	Hg mg/kg NOS	Ag mg/kg FURNACE(a)	As mg/kg FURNACE(a)	Se mg/kg FURNACE(a)	Sb mg/kg FURNACE(a)	Tl mg/kg FURNACE(a)
001	KCL Polymer Mud	26.2	< 1.0	190	246	1,890	0.22	< 3.0	3.96	< 6.0	7.74	0.261	0.089	4.64	< 3.0	4.00	0.078
002	Seawater Lignosulfonate	42.4	< 1.0	1150	74.0	2,060	0.472(b)	764	27.5	< 6.0	1.82(b)	0.264	0.126	2.40	< 3.0	0.260	0.201
003	Lime Mud	37.0	< 1.0	743	41.2	2,170	0.378(b)	908	40.6	< 6.0	1.42(b)	0.753	0.314	17.2	< 3.0	1.06	0.129
004	Non-dispersed Mud	35.9	< 1.0	876	286	1120	0.446(b)	< 3.0	6.78	< 6.0	41.2	0.437	0.228	5.25	< 3.0	0.473	0.114
005	Spud Mud	8.60	< 1.0	347	293	833	0.74(b)	< 3.0	1.61	< 6.0	52.5	< 0.010	< 0.060	0.258	< 3.0	< 0.060	< 0.060
006	Seawater/Freshwater Gel Mud	3.28	< 1.0	536	65.4	392	0.42(b)	< 3.0	0.70	< 6.0	3.51(b)	0.297	< 0.060	0.621	< 3.0	< 0.60	< 0.060
007	Lightly treated Lignosulfonate Mud	2.26	< 1.0	395	408	660	0.142(b)	299	2.86	< 6.0	1.53(b)	0.0961	< 0.060	0.497	< 3.0	< 0.060	< 0.060
008	Lignosulfonate Freshwater Mud	90.4	< 1.0	1150	54.6	5,110	0.36	770	72.2	< 6.0	17.8	0.355	0.244	11.7	< 3.0	0.794	0.071
002-00	Mud 002	42.4	< 1.0	1150	74.0	2,060	0.472(b)	764	27.5	< 6.0	1.82(b)	0.264	0.126	2.40	< 3.0	0.260	0.201
002-01	Mud 002 + 1% Mineral Oil	43.4	< 1.0	1200	71.3	2,520	0.395(b)	740	26.8	7.76	6.83	0.107	0.110	1.47	< 3.0	0.239	0.175
002-05	Mud 002 + 5% Mineral Oil	40.8	< 1.0	1400	144.1	3,350	0.717(b)	720	26.0	9.80	6.20	0.091	0.124	1.70	< 3.0	0.522	0.184
002-10	Mud 002 + 10% Mineral Oil	46.0	< 1.0	955	47.5	2,800	0.470(b)	640	26.1	6.98	1.17(b)	0.072	0.110	1.97	< 3.0	0.160	0.166
008-00	Mud 008	90.4	< 1.0	1150	54.6	5,110	0.36	770	72.2	< 6.0	17.8	0.355	0.244	11.7	< 3.0	0.794	0.071
008-01	Mud 008 + 1% Mineral Oil	86.8	< 1.0	998	1240	4,980	0.18	610	68.9	< 6.0	24.5	0.391	1.39	12.2	< 3.0	2.65	0.080(1)
008-05	Mud 008 + 5% Mineral Oil	65.6	< 1.0	862	27.0	3,940	0.28	541	77.3	< 6.0	13.0	0.368	1.11	9.61	< 3.0	2.70	0.074
008-10	Mud 008 + 10% Mineral Oil	77.8	< 1.0	857	39.5	5,020	0.36	560	42.8	< 6.0	9.48	0.287	1.14	9.24	< 3.0	2.02	0.062(1)

From CENTEC, 1984.

(a) Dry weight basis, average of two samples.
(b) Samples run by HGA.
(1) Single analysis.

NOS = Not Otherwise Specified.

2.2.4.3 Organics

The sole organic pollutant detected via GC/MS analysis for volatile organics, base neutrals, and acid phenols of all the muds was n-dodecane (C-12 alkane) at concentrations ranging from 736 to 899 ppb (μg/kg) (CENTEC, 1984). Addition of mineral oil resulted in dose-dependent detection of n-dodecane, phenanthrene, dibenzothiophene, dibenzofuran, diphenylamine, and biphenyl (Table 2-7).

2.2.4.4 Oil-based Additives for Water-based Muds

A recent industry-sponsored study described the distribution of diesel oil hydrocarbons within base muds and oil additives (Breteler et al., 1984). Mineral, low sulfur, and high sulfur diesel oils were each added to base (generic) mud No. 8 at concentrations of 0.5, 2, and 5 percent. (No solid phase determinations were performed at the 2 percent level). Base mud hydrocarbon concentrations averaged 17.4 ppm total hydrocarbons in the solid phase, compared to 17.1 ppm after 10 days of exposure. Total hydrocarbon concentrations in the mud solid phase following additions of oil did not reflect the amount of oil added.

Total increase in hydrocarbons in solid phase at the 0.5 percent oil addition level were 191, 559, and 415 μg/g for mineral, low, and high sulfur diesel oil, respectively. Approximately 40 percent of these concentrations remained after 10 days of solid phase testing. At the 5 percent addition level, total hydrocarbons in the solid phase increased to 2433, 2923, and 2513 μg/g, respectively. After 10 days of solid phase testing 32 percent, 24 percent, and 36 percent remained,

Table 2-7 RESULTS OF ANALYSIS OF ORGANICS IN DRILLING FLUIDS

RESULTS IN ug/kg (ALL BASE NEUTRAL FRACTION)

EPA ID	Centec ID	Control Center ID	Phenanthrene	Dibenzothiophene	Dibenzofuran	N-Dodecane C-12	Diphenylamine	Biphenyl
001	30854	11487				899		
002	30796	11476						
003	30934	11479				809		
004	30935	11488				819		
005	30855	11480				854		
005	30855	11480 Dup.				822		
006	30856	11481				847		
006	30856	11481 Dup.				802		
007	30797	11477				736		
008	30746	11489				780		
002-01	31055	11486	1060			726		
002-05	31056	11482	8270		827	6540		867
002-10	31057	11484	19300		1040	13300	4280	2290
008-01	31058	11490						
008-05	31059	11485	5580			9380		
008-10	31060	11483	11100		933	8720	5200	1120

From: CENTEC, 1984

respectively. Such losses were nearly complete at the end of 24 hours for mineral oil, whereas the relatively more soluble diesel oils lost a significant portion between 24 and 48 hours.

As expected, the chemical composition of the three oil additives varies drastically (Breteler et al., 1984). Aromatic hydrocarbons comprised 0.4 percent of total hydrocarbons in mineral oil, 8 percent in low-sulfur diesel oil and 29 percent in high sulfur diesel oil. Mineral oils consisted primarily of cycloalkanes and only contained a small amount of n-alkanes. The relative abundance of these alkylated benzenes decreased once the oil was added to the mud, as a result of volatilization during admixing.

If a mixture was stirred for 10 minutes and sampled after one hour, 55 to 82 percent of the C_1 thru C_6 benzenes were lost. If mixing time was increased to 4 hours, 70-100 percent of total added benzenes were lost. Thus any studies looking at drilling mud mixtures containing (added) oil should take into account the amount of time spent mixing, settling, and aerating as well as any "aging" effects.

2.2.4.5 Used Drilling Fluid Samples

The hydrocarbon and metal content of used drilling fluid samples used for toxicity testing (see Section 4) was recently reported by EPA (SAI, 1984 in Duke, 1984). Hydrocarbon content reported as "diesel equivalents" (equivalent to API #2 fuel oil) varied between 0.10 and 9.43 mg/g (Table 2-8). Whole mud contained aliphatic hydrocarbons at levels of 22.4 to 7,230 mg/l, with aromatic hydrocarbons ranging from 11 to 1,600 mg/l. Levels of hydrocarbons in the suspended phase were at

TABLE 2-8 HYDROCARBON CONCENTRATIONS OF DRILLING FLUID SAMPLES

Mud	"Diesel"[1] (mg/g)	Whole Mud[2] Aliphatic (mg/l)	Whole Mud[2] Aromatic (mg/l)	Suspended Particulate Phase[3] Aliphatic (mg/l)	Suspended Particulate Phase[3] Aromatic (ug/l)	Suspended Particulate Phase[3] Polar Fraction (ug/l)	Liquid Phase[4] Resolved (mg/l)	Liquid Phase[4] Unresolved (mg/l)
MIB	0.19	34.5	22.13	0.046	0.073	25.0	0.358	0.813
AN31	1.18	604	292.5	0.325	0.089	497	0.136	1.24
SV76	3.59	1,430	496	3.52	0.912	1,630	0.920	6.63
P1	9.43	6,900	1,600	14.2	5.53	950	0.358	0.603
P2	2.14	1,052	275.6	0.694	0.426	1,380	0.005	0.008
P3	3.98	7,230	675	15.8	2.86	1,120	1.09	6.49
P4	0.67	680	209	0.462	0.442	147	0.002	0.011
P5	1.41	930	390	3.74	1.37	165	0.166	1.16
P6	0.10	22.4	11	0.039	0.038	13.6	0.043	0
P7	0.50	101.3	40.0	0.063	0.030	478	0.175	0
P8	0.56	474	250.9	1.37	1.71	836	0.161	2.42

[1] Values obtained by gas chromatographic/mass spectrometric analyses and external standards (NEA, 1984 as reported in Duke and Parrish, 1984).

[2] Total resolved and unresolved (SAI, 1984 as reported in Duke and Parrish, 1984).

[3] Total resolved and unresolved (SAI, 1984 as reported in Duke and Parrish, 1984).

[4] (SAI, 1984 as reported in Duke and Parrish, 1984).

least two orders of magnitude lower. Levels of polar hydrocarbons in the total suspended phase varied from 13.6 to 1,630 mg/l and were generally the same or lower than the levels of aromatic hydrocarbons. The liquid phase data are uninterpretable as reported. The levels of hydrocarbons observed in the suspended phase are very similar to those observed by Breteler et al., 1984 when up to 5 percent diesel oil or mineral oil was added to generic mud No. 8.

An industry sponsored study (Breteler et al., 1984) showed that total hydrocarbon concentrations in the suspended phase (on an equivalent solids level/oil addition) increase dramatically (up to an order of magnitude) in the series mineral oil < low sulfur diesel oil < high sulfur diesel oil. Total levels of total hydrocarbons dropped drastically (up to 95 percent) during a standard 96-hour LC_{50} test, primarily as a result of volatilization. Test solutions containing the highest level of suspended total hydrocarbons showed the highest relative decrease during the 96-hour test period.

Metal data (see Table 2-9) were highly variable. Whole mud levels were invariably one order of magnitude, and often two orders of magnitude, higher than those in the suspended particulate phase, which in turn were at least one to two orders of magnitude higher than those in the liquid phase. Based upon a review of toxicity data, the only metal for which a correlation may occur is chromium.

2.2.5 Completion and Workover Fluids

Completion and workover fluids are two special types of well treatment fluids. Completion fluids are used during completion of a well, and workover fluids are used when a well is being reworked to increase hydrocarbon production.

TABLE 2-9 METALS CONTENT OF DRILLING FLUID SAMPLES[1]

	DRILLING FLUID SAMPLES																	
	MIB			AN31			SV76			P1			P2			P3		
Element	WM	SP	LP	WM	SP	LP	WM	SP	LP	WM	SP	LP	WM	SP	LP	WM	SP	LP
Al	5.19%	473	0.026	3.74%	1,206	0.079	0.61%	482	0.030	1.01%	555	0.047	0.76%	793	0.009	1.30%	661	0.132
Ba	9.85%	13.9	0.409	21.8%	15	0.469	37.5%	12.5	0.407	36.9%	10.7	0.460	37.2%	8.05	3.32	35.1%	22.9	0.813
Cd	0.387	0.007	0.001	2.38	0.076	0.005	1.62	0.315	0.009	1.85	0.26	0.004	11.8	2.38	0.007	2.10	0.053	0.002
Ca	4.39%	—	—	1.57%	—	—	0.82%	—	—	0.86%	—	—	0.65%	—	—	0.74%	—	—
Cr	337.0	5.76	0.338	774	828	1.15	1,345	457	43.6	814	221	3.34	483	237	0.896	459	138	2.60
Cu	23.4	0.349	0.000	33.6	2.56	0.098	86.1	15.0	1.27	62.3	15.9	0.119	39.7	11.8	0.019	90.4	11.1	0.243
Fe	4.31%	546	0.295	2.68%	1,565	1.09	3.63%	1,975	1.85	3.44%	1,566	1.49	0.70%	1,784	1.27	5.67%	1,810	1.84
Pb	135	1.41	0.011	142	1.20	0.040	151	18.4	0.161	129	13.3	0.093	291	40.6	0.046	100	10.2	0.104
Sr	510	—	—	538	—	—	536	—	—	303	—	—	226	—	—	383	—	—
Zn	161	276	0.001	247	14.5	0.526	495	93.1	0.487	410	52.5	0.075	2,064	338	0.007	439	41.8	0.140

[1] From SAI, 1984 as reported in Duke and Parrish, 1984.
WM = Whole Mud Concentrations expressed as µg/g dry weight, unless otherwise indicated.
SP = Suspended Particulate Concentrations expressed as µg/g wet weight, unless otherwise indicated.
LP = Liquid Phase Concentrations expressed as µg/l wet weight, unless otherwise indicated.

TABLE 2-9 METALS CONTENT OF DRILLING FLUID SAMPLES[1] (Continued)

	DRILLING FLUID SAMPLES														
	P4			P5			P6			P7			P8		
Element	WM	SP	LP	WM	SP	LP	WM	SP	LP	WM	SP	LP	WM	SP	LP
Al	1.56%	1,083	2.41	0.71%	376	0.354	5.10%	1,012	0.021	4.47%	1,010	0.011	0.68%	398	0.026
Ba	48.7%	11.7	10.7	37.5%	15.9	1.04	18.8%	15.8	0.134	21.0%	19.4	0.328	3.00%	15.9	0.302
Cd	8.27	3.06	0.004	2.34	0.075	0.003	10.5	0.556	0.017	0.21	0.018	0.001	0.410	0.024	0.002
Ca	0.18%	—	—	0.57%	—	—	0.19%	—	—	0.46%	—	—	1.54%	—	—
Cr	532	197	41.8	187	34.6	0.513	41.8	1.06	0.227	502	35.6	0.436	480	133	11.0
Cu	32.7	12.3	0.059	126	10.6	0.373	35.1	2.18	0.002	15.6	0.932	0.021	3,448	16.0	0.268
Fe	1.15%	2,896	32.4	7.63%	1,996	1.60	2.51%	1,243	0.108	2.25%	1,001	0.288	1.25%	802.0	1.39
Pb	221	28.2	1.56	104	9.07	0.054	210	10.2	0.003	92.1	1.45	0.004	48.3	5.20	0.199
Sr	207	—	—	346	—	—	120	—	—	258	—	—	1,401	—	—
Zn	1,384	476	0.804	175	27.5	0.007	1,755	80.4	0.007	144	6.30	0.007	144	22.6	0.185

[1] From SAI, 1984 as reported in Duke and Parrish, 1984.

WM = Whole Mud Concentrations expressed as μg/g dry weight, unless otherwise indicated.

SP = Suspended Particulate Concentrations expressed as μg/g wet weight, unless otherwise indicated.

LP = Liquid Phase Concentrations expressed as μg/l wet weight, unless otherwise indicated.

Well completion occurs if a commercial-level hydrocarbon reserve is discovered. The porous rock production zone can be damaged by the mud solids and water contained in normal drilling fluids. To avoid this damage and maximize the production rate, a special low-solids completion fluid may be used to drill through the production zone.

Salts are used in low-solids fluids to inhibit clay swelling and gellation, and to obtain the necessary fluid density without solid weighting materials (Eaton et al., 1981). Sodium chloride, potassium chloride, calcium chloride, calcium bromide, or zinc bromide may be used as weighting materials, depending on the density required. The control of viscosity and filtration rate also requires special consideration in low-solids systems. Organic polymers such as hydroxyethyl cellulose and xanthum gum are used for these purposes. Ground calcium carbonate may also be used to initiate filter cake formation in permeable sand. Corrosion inhibitors, such as amine derivatives, are used in salt systems to reduce damage to casing. At the concentrations used, 0.004 to 0.014 kg/l (1.5 to 5 lb/bbl), these corrosion inhibitors also act as biostats to prevent microbial degradation of polymers. Even so, additional biocides, buffers, defoamers, and other specialty additives may be necessary to maintain suitable drilling conditions.

Workover of a well involves "going back into" an already producing well to increase the rate of hydrocarbon production or reopening a "shut-in" well and reworking to increase productivity to a commercially acceptable level. Workover operations frequently use the fluid left in the well annulus upon completion, which can be either a normal drilling fluid or a low-solids completion fluid (M. Jones, IMCO Services, to T. Mors, Dalton'Dalton'Newport, personal communication, 1982). If the fluid left in the annulus is not appropriate for the workover process, the fluid can be altered or removed and a new drilling mud added.

High solids fluids are used in certain completion and workover operations. They may contain the same materials as typical drilling fluid except that they are freshly formulated to avoid the fine drilled cuttings which accumulate in used drilling fluid. Calcium carbonate or iron carbonate may be used as the weighting material.

Little has been documented concerning the frequency or quantity of completion or workover fluid use. Much of the completion fluid would be left downhole, but the quantities normally discharged are not documented. Similarly, data on workover fluid volumes are lacking. Some data are available on the toxicity of workover fluids to the white shrimp Penaeus setiferus (see Section 4).

2.3 DRILL CUTTINGS

Drilling fluid circulates down the bore hole and back to the surface, carrying drill cuttings with it. The cuttings are removed from the fluid by one of several pieces of solids control equipment. The shale shaker is a vibrating screen that removes large particles from the fluid. Standard shaker screens generally remove particles larger than 440μm (.017 in.), while fine screens can remove particles down to approximately 120μm (.005 in.)(Houghton et al., 1981). The fluid then passes through the sand trap (if used), a gravitational settling tank which removes particles from approximately 75 to 210μm (.003 to .008 in.). The next step, the desilter is a hydrocyclone which uses centrifugal forces to remove silt-sized particles (approximately 5 to 75μm or .0002 to .003 in.). The removed cuttings are discharged anywhere from the platform itself to deep below the water surface depending on the rig, but are typically discharged just above the water surface. The processed drilling fluid is then returned to the mud tanks for recirculation to the well.

Discharges from the solids removal system consist of drill cuttings, wash water used to remove drilling fluid from the cuttings, and drilling mud still adhering to the cuttings (Ray and Meek, 1980). Another study by the same authors (Meek and Ray, 1980) found that discharges from solids control equipment (i.e., cuttings) from a southern California OCS well were composed of 96 percent cuttings solids and 4 percent adhering drilling fluid. However, other data from a mid-Atlantic well placed these values at 40 percent cuttings and 60 percent adhering fluid (Ayers et al., 1980a).

2.3.1 Chemical Characteristics of Drill Cuttings

Only very limited data are available on the physico-chemical characteristics of drilling cuttings, mostly from the Georges Bank program and CENTEC (1984) analysis of three sets of drilling cuttings from three different wells, all at depths greater than 10,000 feet. In Tables 2-10 and 2-11 (A) denotes a cuttings sampling taken prior to washing and (B) a sample taken after washing. Density decreases and pH and water content increase after washing as compared to before washing, although with a considerable range between samples. Oxygen

TABLE 2-10

CONVENTIONAL WATER QUALITY PARAMETERS FOR DRILL CUTTINGS

			pH	Specific Gravity kg/l	% Weight Loss (103°C) (a)	BOD-5 SOW/CAS mg/kg(b)	BOD-5 SOW/POLY mg/kg(b)	UOD-20 SOW/CAS mg/kg(b)	UOD-20 SOW/POLY mg/kg(b)	TOC mg/kg(c)	COD mg/kg(b)	SHEEN TEST 0.5 [1.5g] (15g)(b)	Oil and Grease Sonification mg/kg(b)	Oil and Grease Soxhlet mg/kg(a)
1A	South Timbal Near Block 26 at 9851' w mineral oil	Before Washing	6.50	1.72	18.6	3,500	4,130	9.980	10,500	61,300	190,000	3/3	58,700	69,200
1B		After Washing	7.00	0.98	27.2	8,950	4,290	20,300	26,600	23,000	90,600	[0/3] (3/3)	11,700	108,000
2A	South Marsh Island Block 214 at 14,052' w/Milchem Carbotec	Before Washing	8.42	2.07	15.2	325	1,200	4,210	2,640	64,100	291,000	3/3	60,200	130,000
2B		After Washing	9.82	1.41	20.6	8,800	8,340	21,200	22,800	57,200	272,000	[0/3] (3/3)	46,300	26,600
3A	Vermillion Block 50 at 14,351' with Mayobar Fare-Kleen Mineral	Before Washing	5.70	1.26	9.7	3,750	3,970	6,780	8,170	58,300	198,000	3/3	54,200	73,500
3B		After Washing	9.20	1.59	26.5	8,020	3,890	12,800	16,200	32,000	152,000	[0/3] (3/3)	18,500	8,290

FROM CENTEC, 1984.

(a) Average of 2 measurements.
(b) Average of 3 measurements.
(c) Average of 3 triplicates.

TABLE 2-11 METAL CONCENTRATIONS IN DRILL CUTTINGS

			Zn mg/kg FLAME(a)	Be mg/kg FLAME(a)	Al mg/kg FLAME(a)	Ba mg/kg FLAME	Fe mg/kg FLAME(a)	Cd mg/kg FLAME(a)	Cr mg/kg FLAME(a)	Cu mg/kg FLAME(a)	Ni mg/kg FLAME(a)	Pb mg/kg FLAME(a)	Hg mg/kg ? (a)	Ag mg/kg FURNACE(a)	As mg/kg FURNACE(a)	Se mg/kg FURNACE(a)	Sb mg/kg FURNACE(a)	Tl mg/kg FURNACE
1A	South Timbal - Block 26 at 9851' with mineral oil	Before Washing	2710	< 1.0	7810	84.8	21800	16.4	10.8	55.3	9.40	298	0.0933	0.510	10.3	< 3.0	< 0.060	0.570
1B		After Washing	356	< 1.0	10,500	235	19200	2.15	11.2	20.4	15.9	47.6	0.0920	0.227	7.00	< 3.0	< 0.350	0.228
2A	South Marsh Island Block 214 a 14,052' w/Milchem Carbotec	Before Washing	2030	< 1.0	6020	34.0	16600	10.3	9.48	40.7	12.1	115	0.4893	0.574	10.2	< 3.0	< 0.350	0.339
2B		After Washing	3200	< 1.0	5160	27.2	17400	15.8	12.0	42.6	6.20	264	0.3507	0.568	10.6	< 3.0	< 0.060	0.066
3A	Vermillion Block 50 at 14,351' with Magcobar Face-Kleen Mineral	Before Washing	107	< 1.0	10900	54.0	30800	0.402(b)	11.7	20.6	< 6.00	21.4	0.1476	0.447	7.07	< 3.0	< 0.300	0.235
3B		After Washing	114	< 1.0	7160	84.2	20600	0.408(b)	10.7	26.6	10.4	52.1	0.944	0.222	8.36	< 3.0	< 0.300	0.134

(a) Average of duplicate samples on a dry weight basis
(b) Ibidem HGA analysis.

From Centec, 1984.

demand (as BOD_5 and UOD_{20}) prior to washing is higher than those for drilling muds and increases substantially after washing. In contrast, total organic carbon and chemical oxygen demand either stay the same or drop substantially after washing, as do sheen test results and oil and grease levels. The increased BOD/UOD could indicate several things: the additives used and admixed during washing (detergents) could have high BOD demand, the decrease in "oil" levels allows a better expression of BOD, or washing mechanically disturbs BOD as a result of fine particulate aggregates, increasing surface area and thus cuttings particulates. The latter explanation appears favored, given the results observed by CENTEC (1984) following the addition of oil to generic muds. Oxygen demand increased slightly at low oil levels but decreased oxygen demand (often to levels below those seen at zero percent oil added) when higher levels of oil were admixed. This indicates hydrocarbon toxicity on the organisms used to measure BOD. Note that the sample with the highest TOC, COD, and oil and grease level (2A) has a BOD an order of magnitude lower than any other sample and that BOD/UOD increases dramatically after washing.

Metal levels in cuttings were not of particular notice (Table 2-11). Results mostly appear to indicate the high level of inherent uncertainty of the analyses rather than any actual trends. Metal levels before and after washing appear similar, at least within the bounds of uncertainty. Mercury levels were below 0.5 ppm (dry weight w/w) in all six samples, whereas cadmium levels ranged as high as 16 ppm.

In contrast to drilling fluids, cuttings contained large amounts of base neutral organics (See Table 2-12), which probably derive from added/produced oil. Washing tended to

TABLE 2-12
RESULTS OF GC/MS ANALYSIS OF ORGANICS DRILL CUTTINGS

(Results in ug/kg)

EPA ID	CENTEC ID	CONTROL CENTER ID	(B/N) Acenaphthene	(B/N) Naphthalene	(A) 4-Nitrophenol	(B/N) N-Nitrosodi-phenylamine	(B/N) Bis (2-ethylhexyl) Phthalate
1A	30799	12197	3020				
1B	30802	12199					
2A	30800	12201	38800	149000	30400	56500	
2B	30803	12203	17300	63500		24300	
3A	30801	12205	1020	3582		2870	
3A	30801	12205 Dup.	677	4080		10200	
3B	30804	12207				3150	
3B	30804	12207 Dup.				4110	17300
Blank		12209		10300			

EPA ID	CENTEC ID	CONTROL CENTER ID	(B/N) Phenanthrene	(B/N) Pyrene	(B/N) Dibenzo-thiophene	(B/N) Dibenzofuran	(B/N) N-Dodecane c-12
1A	30799	12197					37300
1B	30802	12199					6310
2A	30800	12201	145000	18900	37300	33700	403000
2B	30803	12203	65700	7860	15000	21700	185000
3A	30801	12205	59900			2150	23000
3A	30801	12205 Dup.	71900			2460	29400
3B	30804	12207	27500				17500
3B	30804	12207 Dup.	25800				18300
Blank		12209					1620

EPA ID	CENTEC ID	CONTROL CENTER ID	(B/N) Diphenylamine	(B/N) Alphaterpineol	(B/N) Biphenyl
1A	30799	12197			
1B	30802	12199		6310	8940
2A	30800	12201	56500		1170
2B	30803	12203	23400		69400
3A	30801	12205			33000
3A	30801	12205 Dup.			4230
3B	30804	12207	7180		4740
3B	30804	12207 Dup.	5900		1840
Blank		12209			2140

FROM: CENTEC, 1984

reduce organic levels by approximately 25 to 60 percent. Polynuclear aromatics were present at high levels (up to over 90 mg/kg) (wet w/w) in cuttings after washing. Naphthalene was detected in the control samples at levels exceeding those in four out of six samples. Aromatic amines were present at levels up to 48 mg/kg. Other chemicals detected included dibenzothiophene, dibenzofuran, n-dodecane (C-12, which was also present in controls), as well as alphaterpene.

2.4 DISCHARGE OF DRILLING FLUIDS AND DRILL CUTTINGS

Discharges from offshore oil and gas drilling operations may be classified as either bulk or "semi-continuous." Bulk discharges originate from the mud tanks and are associated with drilling fluid, whereas so-called "semi-continuous" discharges originate from the solids separation equipment and are associated with drill cuttings. Bulk drilling fluid discharges can be either low or high volume, and occur intermittently during well drilling.

2.4.1 Low Volume Bulk Discharges

Low volume discharges are made to maintain the proper solids levels in fluids, or for cementing operations or well completion. At several points during drilling, the fine, unfilterable particles in the mud will build up and cause excessive viscosity. When this happens, low volume (16-32 m^3) discharges are made and the mud is thinned with water and/or additives (Ayers, 1982).

2.4.2 High Volume Bulk Discharges

High volume discharges occur when:

- drilling fluid must be removed to allow dilution with water
- drilling fluid is being changed from one type to another
- drilling fluid tanks are being emptied at the end of drilling (however, it is possible to save drilling fluid for reuse)

High volume bulk drilling fluid discharges occur several times while drilling a well, and can be at a rate of 250 to 700 bbl/hr or more and last from 20 minutes to three hours. The total discharge per high volume event can be 2,000 barrels or more. For example, bulk mud discharges were at a rate of 700 bbl/hr (maximum volume of 200 bbl) and occurred three times for dilution purposes, and were 700 bbl/hr for up to three hr (maximum volume 2,100 bbl) at the end of drilling for a well in Lower Cook Inlet, Alaska (Houghton et al., 1981). High and low volume discharges of drilling fluids from the mud tanks usually number 20 to 30 during the drilling of a well (G. Petrazzuolo, TRI, to T. Mors, Dalton·Dalton·Newport, personal communication, 1982).

2.4.3 Quantities of Drilling Fluid Discharged

Table 2-13 shows quantities of the basic drilling fluid components used as reported in a survey of 72 recently drilled wells in the Gulf of Mexico (Cole and Mitchell, 1984). Various study deficiencies have been noted since completion of this study that appear to indicate significant underestimation of releases during this study. The average quantity of material used was slightly in excess of 2,000,000 pounds per well, of which more than 90 percent was devoted to basic components. Barite and weighting materials alone accounted for 79 percent of the total, or 1.6 million pounds. Mud usage was observed to increase with depth, as expected, and usage of specialty additive ("Other Components" in Table 2-13) increased sharply in wells deeper than 13,000 feet. Total quantities of basic and specialty components were found to be higher in exploratory wells than developmental wells and higher in wells drilled in Federal waters versus State waters. It should also be noted that the usage of a given component varied considerably from well to well, with standard deviations for all wells in excess of mean values. Maximum values in particular can be seen to exceed mean values by more than an order of magnitude, but means also were exceeded by the standard deviation.

A distinction must be made between the amount of drilling fluid used and the amount actually discharged. Some drilling fluid is always lost to the geologic formation or left in the well annulus at the completion of drilling. Ayers et al., (1982) prepared a materials balance for a Mid-Atlantic drilling operation in which eighty-seven percent of the barite was discharged, six percent was left downhole, and seven percent could not be accounted for. For bentonite plus drilled solids, eighty-nine percent was discharged, one percent was left downhole, and ten percent was unaccounted for. For the combined usage of lignite, chrome lignosulfonate, and cellulose polymer, ninety-five percent of the material was discharged, and five percent was listed as unaccounted for. The amounts unaccounted for are presumed to be lost to the formation and/or left downhole. Other estimates have been made indicating that

TABLE 2-13 AVERAGE MUD CONSUMPTION (lbs) FOR 72 OFFSHORE OIL AND GAS WELLS IN THE GULF OF MEXICO

	Mean	Maximum
Basic Components		
Barite and weighting materials	1,645,613	19,012,499
Bentonite and attapulgite clays	182,517	1,039,699
Lignites and lignosulfonates	72,853	1,048,450
Caustic	33,266	360,000
Soda ash	700	9,999
Lime	5,508	88,750
Sodium bicarbonate	2,118	34,200
Subtotal, Basic Components	1,942,575	
Other Components		
Lost circulation and filtration control materials	26,412	688,900
Lubricants	1,097	38,870
Thinners	117	8,100
Calcium chloride	14,473	345,450
Oil muds	56,583	999,999
Diesel oil	8,802	304,421
Other materials	31,561	630,153
Subtotal, Other Components	139,045	
Total, All Components	2,081,620	

Derived by Cole and Mitchell, based on Cole and Mitchell, 1984.

a much lower proportion of drilling mud (25 to 59 percent) is discharged (Continental Oil Company, 1979). The percentage discharged will vary, of course, depending on the formation and other well-specific characteristics.

2.4.4 Continuous Discharges

"Continuous" discharges are actually frequent, intermittent discharges associated with the operation of the solids control equipment. This equipment operates during drilling, typically one-third to one-half of the time a drilling rig is on-site. Discharges occur from less than an hour to 24 hours per day, depending on the type of operations and the specific well. Various types of continuous discharges are described in Table 2-14. Continuous discharge of drill cuttings has been reported at an average of 10 to 50 bbl/day over the life of a drilling operation (Petrazzuolo, 1981).

Data on drill cuttings production tend to be consistent between wells. The bulk of discharged material (about 2,000 bbl) is generated within the first 1,500 m (5,000 ft) of drilling. Another 2,000 bbl are produced between the 1,500 m (5,000 ft) and 4,000 to 5,000 m (13,000 to 15,000 ft) depth, and by the 6,100 m (20,000 ft) level, discharges have increased by only another 1,000 bbl for a total of approximately 5,000 bbl (Petrazzuolo, 1981).

Approximate quantities of drilled solids for a typical well as calculated by the Bureau of Land Management are presented in Table 2-15. Because the diameter of the drill bit decreases from over 30 inches initially to less than 10 inches at depths of 6,100 m (20,000 ft), the volume of cuttings produced

TABLE 2-14 DISCHARGES FROM SOLIDS CONTROL EQUIPMENT FROM A SINGLE WELL IN LOWER COOK INLET, ALASKA (Atlantic Richfield Company, 1978)

Source	Rate (bbl/hr)	Frequency
Shale shaker	1-2	Continuous during drilling
Desander	3	2-3 hr/day during drilling
Desilter	16-17	2-3 hr/day during drilling
Centrifuge	30	1-3 hr, every 2-3 days
Sand trap	550-2650	2-10 min, every 2-3 days
Sample trap	1.5-3	5-10 min, every 2-3 days

TABLE 2-15 DRILL CUTTINGS FROM TYPICAL EXPLORATION AND DEVELOPMENT WELLS[a]
(BLM, 1977)

Drilling interval		Well diameter		Drill cuttings			
				Exploratory		Development	
				Volume	Weight	Volume	Weight
(m)	(ft)	(cm)	(in)	bbl(m^3)	t (mtons)	bbl (m^3)	t (mtons)
0-46	0-150	90	36	187 (30)	72 (66)	187 (30)	72 (66)
46-300	150-1,000	80	32	846 (135)	332 (302)	846 (135)	332 (302)
300-1,370	1,000-4,500	50	20	1,361 (217)	534 (486)	1,361 (217)	534 (486)
1,370-3,000	4,500-10,000	38	15	1,206 (192)	506 (460)	1,206 (192)	506 (460)
3,000-3,660	10,000-12,000	38	15	439 (70)	184 (167)	—	—
3,660-4,600	12,000-15,000	25	10	291 (46)	131 (119)	—	—
Total				4,330 (690)	1,759 (1,600)	3,413 (543)	1,444 (1,310)

[a] Hypothetical well depths: Exploratory - 4,600m (15,000 ft)
Development - 3,000m (10,000 ft)

decreases as the well depth increases (Petrazzuolo, 1981). The rate of discharge decreases since the speed of drilling slows at greater depths. Petrazzuolo (1981) divides drill cutting discharges into two periods:

- the first 31 percent of the drilling period accounts for 81 percent of the cuttings discharge at an average rate of 89 bbl/day
- the remaining 69 percent of the program accounts for 19 percent of the cuttings discharge at an average rate of 10 bbl/day

Discharge rates for wells in different geographical locations are summarized in Table 2-16. This table shows combined discharges during drilling for both drilling fluid and drill cuttings from four offshore wells.

Total quantities of discharged drilling fluid and drill cuttings increase as well depth increases. The data in Table 2-16 for drill cuttings are illustrative, but hypothetical. The best data for specific wells are from two proposed drilling programs, one from the Shell Oil Company in the Gulf of Mexico, and the other from the Exxon Corporation in the Mid-Atlantic, both reported in Petrazzuolo (1981). Table 2-17 lists the drilling time, mud type, and discharges from these wells according to drilled depth.

Actual data for discharges from eight exploratory wells on Georges Bank are shown in Tables 2-18 and 2-19. Analyses of muds for metals and hydrocarbons at 1,000 foot intervals for a single well on Georges Bank are shown in Table 2-20. The high

TABLE 2-16 SUMMARY OF DRILLING FLUID AND CUTTINGS DISCHARGE RATES BY GEOGRAPHICAL LOCATION

(bbl/day/well)

(adapted from Petrazzuolo, 1981)

OCS location	Drilling fluids	Drill cuttings	Total discharges	Source
Gulf of Mexico	116	47	163	Shell Oil Co., 1978
Mid-Atlantic	190-219	35-40	225-259	Ayers et al., 1980a
Lower Cook Inlet, Alaska	93-203	27-47	120-250	Houghton et al., 1980
Tanner Bank, California	26-28*	7-22*	33-50*	Ecomar, 1978

* Several inconsistencies were noted in the reporting of these quantities.

TABLE 2-17. PROFILE OF PROPOSED DRILLING FLUID AND CUTTINGS DISCHARGES FROM TWO OFFSHORE WELLS

(derived from Petrazzuolo, 1981)

			Drilling Fluid		Cuttings	
Depth interval (ft)	Time (days)	Mud type [a]	Average daily discharge (bbl/day)	Total discharge (bbl) [b]	Average daily discharge (bbl/day)	Total discharge (bbl) [b]
Gulf of Mexico well (Shell Oil Company):						
0-500	1	SW	2,500	2,500	722	722
500-1,000	2	SW	2,500	5,000 (1,000)	289	578
1,000-3,000	6	SWG	200	1,200	265	1,588
3,000-8,000	27	LT FCLS-FW/SW	50	1,350	65	1,757
8,000-16,000	61	FCLS-FW	50	3,050	28	1,733
16,000-20,000	38	FCLS-FW	50	1,900 (800)	10	361
Mid-Atlantic well (Exxon Corporation):						
0-300	1	SW	—	20,000[c] (600)	—	465[c]
300-1,000	2	SWG	850	1,700 (700)	195	390
1,000-4,500	3	LT FCLS-FW/SW	24	72 (2,228)	453	1,359
4,500-12,000	85	FCLS-FW	180	15,300	19	1,615
12,000-15,000	35	FCLS-FW	171	5,985 (1,000)	14	490

[a] Drilling fluid abbreviations:
SW = saltwater plus natural mud
SWG = saltwater plus bentonite or attapulgite
LT FCLS-FW/SW = lightly-treated ferrochrome lignosulfonate freshwater/saltwater system
FCLS-FW = freshwater ferrochrome lignosulfonate system

[b] Numbers in parentheses represent bulk discharges.

[c] Discharged at seafloor, over a 10-hour period, plus 30 bbl excess cement.

Table 2-18 SOLID DRILLING FLUID COMPONENTS USED IN GEORGES BANK DRILLING

Solids (pounds)	L.C. 133 #1	C.C. 975 #1	L.C. 410 #1	L.C. 312 #1	L.C. 187 #1	L.C. 145 #1	L.C. 273 #1	L.C. 357 #1
Barite	1,117,900	774,700	1,124,100	2,387,800	2,651,000	812,200	902,400	2,834,000
Bentonite	496,600	510,600	1,284,300	706,400	1,103,700	689,900	567,800	1,265,400
Caustic Soda	44,150	57,500	87,100	105,600	166,750	35,150	71,050	122,950
Lignite	39,400	37,450	-	54,400	113,200	-	950	-
Chrome Lignosulfonate	46,950	70,400	60,750	36,000	144,350	15,350	11,400	86,350
Sodium Bicarbonate	1,750	8,150	-	-	9,200	-	400	-
Lime	3,950	200	2,650	2,350	2,450	4,100	550	7,550
Sodium Acid Pyrophosphate	550	900	300	-	300	-	-	-
Nut Plug	550	2,250	49,450	950	6,250	-	1,650	41,600
Mica	1,500	2,000	-	-	-	-	-	18,000
Aluminum Stearate	850	-	225	500	50	-	25	425
Drispac	350	3,450	14,150	34,400	39,350	15,500	19,500	17,750
Soda Ash	200	15,000	2,300	7,400	29,600	10,100	12,200	6,300
Salt	-	141,600	-	-	9,760	-	-	-
SULF-XII	-	-	6,500	-	-	-	-	2,350
Poly RX	-	-	-	19,450	-	-	4,500	52,800
Spot	-	-	-	4,550	-	-	-	-
Super-Col	-	-	-	-	69,800	-	-	-
Chemtrol-X	-	-	-	-	99,750	-	-	-
Super Shale Trol 202	-	-	-	-	21,950	-	-	-
XC Polymer	-	-	-	-	150	-	-	-
WO 30	-	-	-	-	100	-	-	-
Calcium Chloride	-	-	-	-	-	-	-	5,400

Table 2-19 LIQUID DRILLING FLUID COMPONENTS USED IN GEORGES BANK DRILLING

Liquids (gallons)	L.C. 133 #1	C.C. 975 #1	L.C. 410 #1	L.C. 312 #1	L.C. 187 #1	L.C. 145 #1	L.C. 273 #1	L.C. 357 #1
Foam Ban	-	-	30	-	-	-	-	-
Torque Trim	-	-	-	660	-	-	165	-
Lube 106	-	-	-	160	-	-	700	-
MD	-	-	-	10	455	-	-	-
Diesel Fuel	-	-	-	4,284	-	-	-	-
Free Pipe	-	-	-	110	-	-	-	-
Scale Ban	-	-	-	-	15	-	-	-
LD-8	-	-	-	-	2,225	-	-	-
WO Defoamer	-	-	-	-	95	-	-	-
Aqua Spot	-	-	-	-	1,265	-	-	-
Mentor 28	-	-	-	-	275	-	-	-

L.C. - Lydonia Canyon

C.C. - Corsair Canyon

Table 2-20 CUTTINGS ANALYSIS, DISCHARGE 002

BLOCK: MOBILE GB: 0027006

DEPTH IN 1,000' INCREMENTS

	1	1.2	2	2.3	3	4	5	6	7	8	9	10	11	12	13
Mud Density, lbs/gal	13.55	14.51	13.55	8.07	14.88	14.45	13.33	9.83	14.60	14.56	15.09	10.90	16.34	15.80	16.28
METALS ANALYSIS															
Arsenic, PPM															
Barium, Per Cent						.15	.74	.14	.13						
Cadmium, PPM	.34	.23	.20	.01	.23	.15	.27	.03	.30	.22	.22	.13	.36	.27	.18
Chromium, PPM	.58	.47	.41	.19	3.86	50.00	20.00	29.00	23.00	96.00	63.00	65.00	91.00	36.00	65.00
Copper, PPM	.23	.23	.20	.01	.80	13.40	11.50	2.90	17.80	16.10	25.80	15.00	48.30	20.50	20.70
Lead, PPM	4.40	4.51	3.99	4.89	5.21	31.00	42.00	94.00	17.00	20.00	18.00	14.00	49.00	20.00	144.00
Mercury, PPM	.06	.07	.14	.01	.04	.03	.02	.01	.04	.03	.03	.02	.02	.03	.03
Nickel, PPM	12.30	15.60	12.50	.86	15.23	38.00	10.00	1.80	41.00	31.00	37.00	22.00	71.00	34.00	33.00
Xanadium, PPM						72.00	29.00	5.00	67.00						
Zinc, PPM	30.00	34.00	15.00	3.10	34.00	68.00	59.00	9.80	80.00	67.00	75.00	38.00	121.00	48.00	50.00
Iron, PPM	119.00	44.00	15.00	.69	282.00	34,672.00	18,553.00	1554.00	31,000.00	21,652.00	33,162.00	16,775.00	52,363.00	26,727.00	27,856.00
Aluminum, Per Cent						4.29	2.61	.53	4.54						
HYDROCARBON ANALYSIS															
Extract wt. mg/l	172.80	184.60	18.30	6.60	129.40	316.00	797.00	166.00	914.00	187.00	136.00	63.00	151.00	169.00	307.00
Aliphatics, F_1, mg/l	48.30	145.00	0.00	6.80	0.00	62.00	183.00	0.00	0.00	98.00	113.00	63.00	131.00	92.00	61.00
Aromatics, F_2, mg/l	0.00	0.00	0.00	4.00	0.00	161.00	264.00	18.00	33.00	89.00	11.00	7.00	48.00	33.00	118.00
Aromatics, F_3, mg/l	0.00	52.00	44.00	.40	0.00	7.40	49.00	10.00	15.00	6.00	5.00	2.00	11.00	1.00	7.00
Sum $F_1 + F_2 + F_3$	48.30	197.00	44.00	11.20	0.00	230.40	496.00	28.00	48.00	193.00	129.00	72.00	190.00	126.00	186.00
% Recovery*	28.00	107.00	240.00	170.00	0.00	73.00	62.00	17.00	5.00	103.00	95.00	114.00	126.00	75.00	61.00

* (Sum/Ext. wt.)

levels of iron that occur from 5,000 feet depth on down appear mostly due to iron in the cuttings from the formation rather than added iron from the drilling fluid.

There are two basic types of offshore oil and gas wells. Exploratory wells can be defined as those drilled from movable structures such as mobile drilling ships or semi-submersible rigs. Developmental (also referred to as "production") wells are those drilled from permanent platforms. Anywhere from a dozen to as many as one hundred developmental wells may be drilled from a single production platform, although 25 is probably a reasonable average for a modern production platform. While every well will be different, exploratory wells are thought to be drilled somewhat deeper than developmental wells. However, reported data do not clearly support this assumption (See Section 1.2, pp. 1-8 to 1-12). Typical offshore well depths (in the Gulf of Mexico) are approximately 10,000 ft (See Section 1.2).

2.4.5 Oxygen Demand of Discharges

The high oxygen demand of discharged drilling fluids and cuttings raises concern regarding its impact on dissolved oxygen levels in offshore waters, especially in shallow areas, poorly mixed areas, areas subjected to episodic (oxygen) depletion, and/or heavily developed offshore areas. To assess this concern, an oxygen demand mass balance for discharged drilling fluids and cuttings has been developed. Other discharges from drilling rigs/platforms have an oxygen demand (e.g., sanitary wastes, domestic wastes), but the oxygen demand of these discharges has not been assessed (the oxygen demand of produced water is discussed below).

The mass balance was developed from these scenarios: (1) a low estimate scenario calculated from the lowest realistic volume discharged mud at the lowest BOD/UOD levels; (2) a mean estimate scenario, where volume and BOD/UOD data represent average values; and (3) a high estimate scenario where the upper estimates for these data were used.

Four separate sources of BOD/UOD were considered: Drilling muds with a lubricant added (mineral oil); muds without added oil; drill cuttings from muds with a mineral oil lubricant; and cuttings from muds without oil. Assuming drilling mud volume estimates contained in the NRC report (1983) represent the range of discharge values (5,000 to 30,000 bbl/well), one can estimate a low, median, and high value of 5,000 bbl/well, 15,000 bbl/well, and 30,000 bbl/well. A lubricant is assumed to be used for about 50 percent of the well. Therefore, 50 percent of the drilling fluid contained 5 percent added mineral oil; the remaining 50 percent contained no added oil.

For "clean" cuttings, an oxygen demand of zero was assumed. Although, given the oxygen demand associated with "clean" cuttings from nutrient content, these discharges will have a BOD. At present, however, this oxygen demand has not been quantified. Therefore, a BOD/UOD of zero for oil-free and mud-free cuttings was assumed, while acknowledging that this could substantially underestimate the total oxygen demand of discharged cuttings.

For cuttings from mud systems, the assumption was made that the adherent mud would be 5 percent of the cuttings, by weight. This assumption produces a BOD/UOD equivalent to 5 percent of that for the cuttings-associated drilling mud.

Therefore, BOD/UOD values were derived from muds that contained no added mineral oil and mud that contained five percent mineral oil. Cuttings discharges were assumed to be 1000 tons (kkg) for all scenarios; it was assumed that lubricants would be needed latter in the drilling program, thus 650 tons were considered from non-oil-contaminated mud systems and 350 tons from oil-contaminated muds.

Given the inhibition by oil of BOD/UOD measurements as discussed above, a correction for oil inhibition was made on the BOD/UOD data for oil-contaminated mud and cuttings (Table 2-21), BOD/UOD for 5 percent mineral oil mud was calculated as equivalent to 5 X BOD/UOD for 1 percent mineral oil mud. Based on these data, a correction factor for BOD 5 percent [calculated]/BOD 5 percent [measured] was obtained that was applied to the oily cuttings. Given that the oil and grease levels in oily cuttings generally exceeded 5 percent, this factor may be an undercorrection. The average BOD for oily and non-oily mud discharges calculated in this fashion is 5,365 mg/kg. This value agrees very well with the average BOD for mud discharges of 5,000 mg/kg derived by industry contractors (see Breteler et al., 1984).

These results were used to calculate the oxygen demand mass balance (See Table 2-22), and resulted in a median, one-well scenario, total BOD estimate of 32,940 kg, with low estimate and high estimate scenarios of 7,680 kg and 84,950 kg, respectively. Total BOD contained in mud discharges averaged 23,500 kg per well, with a range of 3,050 kg to 73,930 kg BOD. Total BOD in cuttings contributed 9,360 kg BOD to the median scenario with a range of 4,630 kg to 11,020 kg BOD. The median UOD estimate scenarios for one well is 76,270 kg, with a range

TABLE 2-21 SUPPORTING CALCULATIONS FOR OXYGEN DEMAND VALUES IN THE PRESENCE OF OIL[a]

		Low	Medium	High	
Mud	BOD 1%	1,373	1,850	2,383	MG/KG
	BOD 5% (calc)[b]	6,860	9,240	11,920	MG/KG
	BOD 5% (meas)	2,023	2,450	3,416	MG/KG
	BOD calc/meas	3.39	3.77	3.49	
	UOD 1%	4,073	4,650	5,803	MG/KG
	UOD 5% (calc)[b]	20,365	23,240	29,015	MG/KG
	UOD 5% (meas)	6,942	8,132	9,773	MG/KG
	UOD calc/meas	2.93	2.86	2.97	
Cutting	BOD (meas)	3,890	7,050	8,950	MG/KG
	BOD (calc)	13,190	26,580	31,240	MG/KG
	UOD (meas)	12,800	19,980	26,600	MG/KG
	UOD (calc)	37,500	57,140	79,000	MG/KG

Footnotes:

[a] Based on Centec, 1984 data

[b] BOD 5% calculated as 5 x (BOD 1%)

TABLE 2-22 COMPARISON OF MEASURED AND CALCULATED BOD VALUES IN THE PRESENCE OF OIL

			Volume	Density (g/ℓ)	BOD mg/kg Concentration	UOD mg/kg Concentration	COD mg/kg	Total BOD Mass (kg)	Total UOD Mass (kg)	Total COD Mass (kg)
Mud Discharges	Nonoil	Low[a]	2,500 bbl	1.09	180	130	1,800	80	60	780
		Median[b]	7,500 bbl	1.84	1,690	2,820	27,860	3,730	6,230	61,510
		High	15,000 bbl	2.15	2,740	4,220	41,200	14,140	21,780	212,590
	Oil (5% Oil)	Low[c]	2,500 bbl	1.08[f]	6,870	20,370	75,300	2,970	8,800	32,530
		Median[c]	7,500 bbl	1.79[f]	9,240	23,250	86,800	19,850	49,940	186,450
		High[c]	15,000 bbl	2.09[f]	11,920	29,020	98,300	59,790	145,560	493,070
	Total	Low	5,000 bbl	1.08	NA	NA	NA	3,050	8,860	33,310
		Median	15,000 bbl	1.82	NA	NA	NA	23,580	56,170	247,960
		High	30,000 bbl	2.12	NA	NA	NA	73,930	167,340	705,660
Cuttings	Nonoil (5% Mud)	Low[d]	650 tons		9	6	36	6	4	20
		Median[d]			85	141	1,393	55	92	910
		Method[d]			137	211	2,060	89	137	1,340
	Oil	Low[e]	350 tons		13,190	37,500	90,600	4,620	13,130	31,710
		Median[e]			26,530	57,140	171,530	9,300	20,000	60,040
		High[e]			31,240	79,000	272,000	10,930	27,650	95,200
	Total	Low	1000 tons		NA	NA	NA	4,630	13,130	31,730
		Median			NA	NA	NA	9,360	20,100	60,950
		High			NA	NA	NA	11,020	27,800	96,540
Total Discharge	Total	Low						7,680	21,990	65,040
		Median						32,940	76,270	308,910
		High						84,950	195,140	802,200

[a] Values represent average of available data for generic Mud 006.

[b] Values represent average of available data for generic Muds 001, 002, 003, 007 and 008.

[c] Data for 5% oil are calculated from 1% oil.

[d] Assumes no oxygen demand in cuttings and are 5% of oxygen demand data reported for Nonoil Muds shown above.

[e] Data are corrected for oil content based on ration of actual measured BOD values for 5% oil Muds - See also Table 2-22.

[f] Densities are the densities for nonoil muds corrected for oil density assuring d of 0.85 for oil

of 21,990 kg to 195,140 kg. The range estimates are narrow, given the deliberate variabilities of the assumptions. Also, both the corrected BOD and UOD estimates are much lower than the theoretical maximum oxygen demand value, based on COD, which is estimated at an average of 308,910 kg with a range of 65,040 kg to 802,200 kg.

Assuming an average drilling program of 60 days, the average well will discharge approximately 550 kg BOD daily. Using an annual activity of 1464 offshore wells (API 1983) at 33 tons (kkg) BOD per well, the total industry BOD discharge from (offshore) oil and gas drilling activities results in a mean annual estimated discharge of 48,300 tons, or an average of 132 tons BOD per day. The low and high estimates, if annualized industry-wide, are 11,300 tons BOD per year and 124,000 tons BOD per year, respectively. Average daily low and high estimates, respectively, are 30 tons BOD per day and 340 tons BOD per day. Average total UOD and COD demand are, expectedly, higher: 111,630 tons and 452,376 tons per year.

The BOD estimate for muds and cuttings can be compared to that of sewage sludge. The estimated total input from ocean disposal of domestic sewage in 1980 was 7.3×10^6 tons (NRC, 1983). The BOD of sewage sludge approximates 1,000 mg/kg; its COD is approximately twice its BOD. Therefore, the BOD input from ocean disposal of sewage sludge approximates 7,300 tons per year (NRC, 1983). Thus, BOD from ocean discharge of drilling muds and cuttings is more than six times that of ocean disposed sewage sludge, while the COD is more than 30 times higher.

2.5 PRODUCED WATER

Water brought up from the hydrocarbon-bearing strata with the produced oil and gas includes brines trapped with the oil and gas in the formation and possibly water injected into the reservoir to increase productivity. (Water injected to increase hydrocarbon recovery is normally injected into wells other than the producing wells). This trapped water is called produced water, or formation water, process water, or brine, and constitutes the major waste stream by volume from the production phase of offshore oil and gas activity. Produced waters are classified into three groups--meteoric, connate, and mixed waters.

Meteoric water is water that has fallen as rain and has filled up the porous and permeable shallow rocks or has percolated through them along bedding planes, fractures, and permeable layers. The presence of carbonates, bicarbonates, and sulfates in oil field water suggests that part of this water has come from the surface and is meteoric. Connate water originally denoted the fossil seawater in which marine sediments were originally deposited; presumably, originally filling all pore spaces. Current usage uses the definition connate water is that interstitial water existing in the reservoir rock prior to the disturbance of that rock by drilling. Most connate waters are brines, characterized by an abundance of chlorides, particularly sodium chloride (NaCl), and have concentrations of dissolved solids many times greater than that of common seawater. Mixed waters are characterized by both a high chloride and sulfate-carbonate-bicarbonate content. This suggests a multiple origin--presumably meteoric water mixed with or partially displaced by the connate water of the rock (DOI, 1982b).

The amount of produced water that is generated is dependent upon the method of recovery and the nature of the formation. In some formations, water is generated with the oil and gas in the early stages of production; in others, water is not produced until the formation has been significantly depleted; and in some, water is never produced. The quantities of produced water that may be discharged vary considerably among platforms, and can be comparatively large for central processing facilities. At the Buccaneer Field, where one of the major field studies on the effects of production operations was conducted, produced water discharge was estimated to be 600 bbl/day (95.3 m^3/day) (Middleditch, 1981). Produced water discharges estimated for the EPA verification 30 platform study ranged between 134 bbl/day-150,000 bbl/day (21-23,835 m^3/day) and averaged 4,011 bbl/day (637 m^3/day) excluding central processing facilities and 9,577 bbl/day (1,522 m^3/day) including these facilities. The discharge for the Trading Bay Facility in Alaska was estimated to be 62,000 bbl/day (9,852 m^3/day) (Lysyj, 1981). The produced water may be discharged either above or below the water surface. In some cases, the water is piped to shore for onshore injection or treatment; in other instances, the water may be reinjected offshore either for disposal or pressure maintenance purposes.

2.5.1 Chemical Characteristics of Produced Water

Most produced waters are brines, characterized by an abundance of sodium chloride, other chlorides, and dissolved solids in concentrations several times greater than in seawater. Approximately 61 percent of the mineral matter is comprised of chlorides. Chlorides in produced water from ten platforms in the Gulf of Mexico were in the range 37,000 -

110,000 ppm (Jackson et al., 1981); normal values for seawater are around 19,000 ppm. Other major mineral components include 34 percent sodium, three percent calcium, and two percent other materials. Suspended and settleable solids are also present.

After passing through an oil-water separator, produced water from oil and gas operations off the U.S. coast is usually discharged into the sea or, in some cases, is reinjected for disposal or pressure maintenance purposes. This produced water contains hydrocarbons, metals, as well as other organic and inorganic constituents. Data on the oil content of produced water were obtained for ten platforms in the Gulf of Mexico off Louisiana (Jackson et al., 1981). For this study, the infrared method of measuring oil content gave average values of 15-106 ppm and the gravimetric method, 7.6-77 ppm (Table 2-23). Note the extremely high standard deviations of this measurement.

2.5.1.1 Organics

Lower molecular weight hydrocarbons are more soluble in seawater than the higher molecular weight hydrocarbons and, therefore, are preferentially partitioned from the produced oil and gas into produced water. The lower molecular weight hydrocarbons include the volatile liquid hydrocarbons (VLH) in the C_6 to C_{14} range. These are important from an environmental standpoint, since they include the light aromatics (benzene through naphthalene) that are among the most immediately toxic components of petroleum. Information on the concentrations of these hydrocarbons in produced waters is presented in Tables 2-24 and 2-25.

TABLE 2-23 PLATFORM FLOTATION EFFLUENT OIL CONTENT
COMPARISON FOR GULF OF MEXICO OFF LOUISIANA

Platform	GR-Oil, mg/l Average (SD)	IR-Oil, mg/l Average (SD)	"Dispersed" Oil, mg/l Average (SD)	"Soluble" Oil, mg/l Average (SD)	"Soluble" Oil, fraction of IR-Oil (%)
SS107	7.6 (5.2)	15 (3.7)	1.6 (1.5)	13 (2.7)	87
SS198G	18 (9.2)	36 (7.8)	5.7 (7.7)	31 (2.7)	86
BDCCF5	26 (6.9)	36 (8.3)	26 (8.6)	10 (2.3)	28
ST131	12 (13)	37 (19)	5.9 (13)	28 (3.1)	76
BM2C	22 (6.7)	39 (4.2)	4.9 (5.1)	36 (4.1)	92
SM130B	48 (16)	48 (16)	23 (13)	25 (4.7)	52
EI18CF	52 (24)	76 (38)	63 (30)	13 (13)	17
WD45C	63 (95)	81 (109)	66 (106)	30 (32)	37
ST177	64 (74)	95 (103)	92 (126)	21 (13)	22
SP65B	77 (73)	106 (99)	38 (80)	61 (15)	58

Note: Some numbers do not check because of rounding. Two significant figures have been retained in all numbers below 100.

SD = Standard Deviation.
GR = Gravimetric method.
IR = Infrared method.

Source: Jackson et al., 1981.

TABLE 2-24 LOW MOLECULAR WEIGHT HYDROCARBONS IN PRODUCED WATER FROM THE BUCCANEER GAS AND OIL FIELD

Compound	Mean	Range
Light hydrocarbons (ml/l)		
Methane	2,413	960 - 4,910
Ethane	408	140 - 680
Propane	237	69 - 400
Iso-butane	98	23 - 190
Butane	81	19 - 197
Iso-pentane	113	39 - 219
Pentane	98	38 - 203
Total Light Hydrocarbons	3,450	
Volatile hydrocarbons (μg/l)		
n-Hexane	40	20 - 80
n-Heptane	50	21 - 100
n-Octane	74	19 - 130
n-Nonane	89	16 - 200
n-Decane	154	39 - 400
n-Undecane	260	18 - 880
n-Dodecane	290	35 - 1,000
n-Tridecane	324	48 - 1,050
n-Tetradecane	476	64 - 1,410
Benzene	9,500	5,600 - 17,700
Cyclohexane	221	82 - 400
Methylcyclohexane	190	62 - 340
Toluene	4,575	2,600 - 8,500
Dimenthylcyclohexane	88	48 - 140
Ethylbenzene	533	220 - 1,100
m, p-Xylene	1,043	500 - 1,900
o-Xylene	990	480 - 1,800
Total n-C_6-C_{14}	1,760	420 - 5,100
Total aromatic	16,675	10,000 - 31,100
Total Volatile Liquid Hydrocarbons*	21,600*	11,300 - 44,400

*Unresolved error in total addition.

Adapted from Brooks et al., 1980.

TABLE 2-25 VOLATILE LIQUID ALIPHATIC HYDROCARBONS IN PRODUCED WATER DISCHARGES FROM THE BUCCANEER FIELD IN THE GULF OF MEXICO

	Concentration (ppb)	
Component	Middleditch (1980)	Sauer (1981)
2-Methylbutane	960	ND
n-Pentane	720	ND
Methylcyclopentane	460	50
2-Methylpentane	ND	1,520
3-Methylpentane	80	ND
2,2-Dimethylpentane	ND	50[a]
2,2,3-Trimethylpentane	ND	170
1,3-Dimethylcyclopentane	240	ND
1-Methyl-(1 or 3)-ethylcyclopentane	ND	50
n-Hexane	460	70
3-Methylhexane	200	ND
2,2-Dimethyl-3-hexene	160	ND
Cyclohexane	520	100
Methylcyclohexane	1,080	210
Dimethylcyclohexanes	200	120
Trimethylcyclohexane	80	ND
Ethylcyclohexane	ND	230
n-Propylcyclohexane	ND	230
Alkylcyclohexane	ND	70
Heptanes	580	680[b]
Octanes	120	620[b]
Octene	380	ND
Octadiene	40	ND
n-Nonane	ND	520
n-Decane	ND	410
n-Undecane	ND	310
n-Dodecane	ND	140
n-Tridecane	ND	110
n-Tetradecane	ND	50
Branched alkane	ND	10
Branched alkane	ND	20
Methyl ethyl ketone	300	70
Methyl propyl ketone	ND	570
Diethyl ketone	ND	300
Methyl isobutyl ketone	ND	190
2-Pentanone	160	ND

[a] The spectrum for 2,2-Dimethylpentane is similar to that of 2,2,3-Trimethylbutane.

[b] The spectrum of 3-Methylheptane (130 ppb) is similar to that of 2,5-Dimethylhexane; the spectrum of 2,6-Dimethylheptane (150 ppb) is similar to that of 2-Methyloctane.

Brooks et al., (1980) obtained a mean VLH concentration of 21.6 ppm in produced waters from an oil and gas production platform in the Buccaneer Field in the Gulf of Mexico off Texas (Table 2-24); Sauer (1981) obtained a similar value for this field. Over 80 percent of the VLHs in the produced water consisted of light aromatic compounds, with benzene, toluene, ethylbenzene, and m-, o-, and p-xylenes predominating.

Similar concentrations of light aromatic hydrocarbons have been detected in produced waters from a number of other platforms in the Gulf of Mexico and Alaska (Table 2-26). Included among these is the EPA verification study for 30 platforms in the Gulf of Mexico (EPA, 1982). A companion study was conducted for the Offshore Operators Committee by Radian (1982) on duplicate samples taken from six of the 30 platforms sampled during the EPA study; both sets of analyses were subject to extensive quality control procedures. In addition, EPA funded an earlier Rockwell International study of produced water (Lysyj et al., 1982). The only one of these programs involving analyses of samples from an area other than the Gulf of Mexico was that of Lysyj et al. (1982). They found that the average concentration of BTX compounds in treated effluents discharged to Cook Inlet, Alaska, was 9.1 ppm. Benzene was the predominant VLH compound in each of the studies.

Produced water from the Buccaneer Field was analyzed for methylnaphthalenes, which are two-ring aromatic hydrocarbons. The mean concentration of these compounds was 43 ppb with a maximum of 170 ppb. Naphthalene concentrations measured during the EPA verification 30 platform study in the Gulf of Mexico ranged between 19 and 1454 ppb and averaged 187 ppb. For a set of duplicate samples from six of these platforms, Radian (1982)

TABLE 2-26 SUMMARY OF CONCENTRATIONS OF LIGHT AROMATIC HYDROCARBONS FOUND IN PRODUCED WATERS BY RECENT STUDIES

	Concentration (µg/l)									
	EPA Verification Study for 30 Platforms (Gulf of Mexico)		Radian Analysis for Six of 30 Platforms in EPA Study (Gulf of Mexico)		Buccaneer Field Gulf of Mexico (Brooks et al., 1980)		Seven Facilities Gulf of Mexico (Lysyj et. al., 1982)		Three Facilities Alaskan Waters Lysyj et. al., 1982)	
Compound	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
a. Aromatic Hydrocarbons										
Benzene	2,977	2-12,150	3,500	170-16,000	9,500	5,600-17,700	1,100	400-2,400	5,500	3,700-6,500
Toluene	2,007	60-19,800	2,400	150-8,600	4,575	2,600-8,500	800	400-2,100	2,700	1,900-3,400
Ethylbenzene	431	6-6,010	230	27-560	533	220-1,100	NS	—	NS	—
Naphthalene	187	19-1,454	150	17-440	NS	—	27[a]	ND-44	NS	—
m,p-Xylene	NS	—	NS		1,043	500-1,900	NS	—	NS	—
Xylenes/Ethylbenzene	NS	—	NS		NS	—	300	200-300	900	500-1,300

[a] Detected in three wells; average includes only detected concentrations.

NS - Not sampled.

ND - Not detected.

reported that average concentrations of naphthalene ranged between 17-440 ppb. It should be noted that the EPA and Radian analyses were limited to "priority pollutants" that include naphthalene but not the alkylated derivatives. Thus, these analyses do not reflect the total quantity of naphthalenes present.

Produced water also contains higher molecular weight aliphatic and aromatic hydrocarbons. Middleditch found that the mean concentration of heavier saturated hydrocarbons (C_{12} - C_{38}) in produced water from the Buccaneer Field was 3.4 ppm with occasional observations as high as 12 ppm.

At present, there are little quantitative data on concentrations of polynuclear aromatic hydrocarbons (PAHs) in produced water. In the EPA 30 platform verification study, benzo[a]pyrene was detected in three out of 73 samples. Concentrations in these three samples were 4, 15, and 19 ppb. Data from the Buccaneer Field study indicated that produced water benzo[a]pyrene concentrations ranged up to 5 ppb with a mean concentration of 1.2 ppb (Middleditch, 1981). This is consistent with the EPA study and suggests that benzo[a]pyrene is present in produced waters at low (ppb) levels.

2.5.1.2 Inorganics

Inorganic compounds present in produced waters include heavy metals. However, as noted by Menzie (1982) and Middleditch (1984), there has been uncertainty about the quality of the data. This is in part due to the difficulty in analyzing metals in heavy brine solutions. Work was conducted at a single platform in the Buccaneer Field by Anderson et al.,

(1979) and by Tillery (1980), but results from this study have shown wide discrepancies and do contain typographical errors (Middleditch, 1984). Therefore, this report includes data from three studies that sampled produced water from a number of platforms in the Gulf of Mexico. These include the EPA 30 platform verification and the companion Radian (1982) studies, and the Lysyj et al., (1982) study (Table 2-27). These all show generally similar ranges in concentrations of selected metals in produced water.

An interesting component in produced water from the Buccaneer Field that Middleditch (1981) observed was the presence of elemental sulfur. He determined the concentration of sulfur by a gravimetric procedure and found a maximum concentration of 1200 ppm and a mean concentration of 460 ppm. Other inorganic chemicals that may be present include ammonia and hydrogen sulfide. For a project off Santa Barbara, ADL (1984) reported that concentrations of these two compounds could reach 800 mg/l and 100 mg/l, respectively.

2.5.1.3 Radioactivity

Radioactive materials such as radium also are found in some oil field produced waters, having leached from the shales and sandstones of the geologic formation (EPA, 1978). Open ocean surface waters normally contain 0.05 pCi/liter of radium. Radionuclide data for filtered and unfiltered produced waters from Gulf Coast drilling areas have shown Ra-226 concentrations ranging from 16 to 393 pCi/liter, with a median of 254 pCi/liter, while Ra-228 content ranged from 170 to 570 pCi/liter (Table 2-28). The filtered produced waters were only slightly lower in radium content (EPA, 1978). These levels of

TABLE 2-27 HEAVY METAL CONCENTRATIONS IN PRODUCED WATER

	Concentrations in ppb					
Metal	EPA Verification Study 30 Platforms Gulf of Mexico		Radian Study for six of the Platforms		Multi Platform Study Gulf of Mexico (Lysyj et al., 1982)	
	Mean	Range	Mean[d]	Range	Mean	Range
Antimony					ND	
Arsenic					ND	
Beryllium					2.7[a]	2-4
Cadmium	5.1	ND-98	4	ND-25	48.3[a]	39-56
Chromium			14	ND-15	260	59-390
Copper	81.9	ND-1455	ND	ND-140	124.7	100-137
Iron						
Lead	115.7	ND-5700	300	ND-800	597	160-915
Mercury					0.4[b]	—[b]
Nickel	25.9	ND-276	90	ND-160	1,195[c]	68-1674
Selenium					ND	
Silver	8.1	ND-107	ND	ND	111[a]	72-108
Strontium						
Thallium					ND	
Zinc	168	5-519	98	28-320	351[c]	190-640

ND - not detected

[a] Detected in three out of seven wells; average includes only detected concentrations.

[b] Detected in one out of seven wells.

[c] Detected in four out of seven wells; average includes only detected concentrations.

[d] Means are those calculated by Middleditch (1984).

TABLE 2-28 RADIUM CONTENT OF SOME GULF COAST OIL FIELD PRODUCED WATER

Oil Field Identification	Ra-226 (pCi/1)	Ra-228 (pCi/1)
Bay de Chene, LA	327 ± 5	426 ± 26
Houma District, LA	131 ± 3	170 ± 11
Lafayette District, LA	298 ± 5	328 ± 20
Grand Island District, LA	144 + 4	202 ± 13
Garden Island Bay, LA	393 ± 7	570 ± 34
Grand Bay, LA	183 ± 4	—
Leeville, LA	321 ± 20	385 ± 30
Leeville, LA	254 ±12	318 ± 22
Empire, LA	199 ± 6	—
High Island, TX	313 ± 4	407 ± 29
Pelican Island, TX	16 ± 5	—

Based on DOI 1982b.

radioactivity are significantly higher than background levels. Research has suggested that there is a relationship between the salinity of formation waters and their radium content. Formation waters of increased salinity appear to have increased Oadium content (Dr. David F. Reid to C. Mitchell, Dalton˙Dalton˙Newport, personal communication, 1983).

The Office of Radiation Programs in EPA has performed some preliminary health physics calculations to estimate the potential for public health consequences from the radium content in these discharges. These preliminary hypothetical calculations indicate that a radiation dose to humans from the consumption of seafood containing Ra-226 or Ra-228 from produced water is approximately 1.0 mrem/yr or less, and this is well below the allowable levels for humans based on international guidelines of 500 mrem/yr.

The Office of Radiation Programs is initiating a one year study at the University of Rhode Island MERL facility to assess partitioning of Ra-226 in the marine ecosystem and its biological uptake. EPA is also involved in the International Atomic Energy Agency (IAEA) Advisory Group for defining "de minimus" levels of naturally occurring and man-made radionuclides for purposes of the London Dumping Convention.

2.5.1.4 Priority Pollutants

The EPA 30 platform verification study involved analyses of priority pollutants. Data on the concentrations of aromatic hydrocarbons and metals have already been presented. Two additional priority pollutants which were detected in the produced water were 2,4-dimethylphenol and phenol. Concentrations of these chemicals are given below.

Chemical	Mean (ppb)	Range (ppb)	No. Samples Where Not Detected	Total No. Samples
2,4-Dimethylphenol	200[a]	ND - 3,504	5	63
Phenol	2,343	65 - 20,812	0	63

[a] Mean of 58 samples where chemical was detected.

Possible mass loadings of selected priority pollutants in produced water to the marine environment were estimated based on discharge volumes and pollutant concentrations (Table 2-29). The estimates indicate that annual loadings of the chemical benzene could exceed 25 metric tons (70 kg/day) for large discharges. For average platforms (based on the verification study), loadings could reach a few kg/day for several of the priority pollutants examined.

2.5.1.5 Conventional Parameters

Produced water may also contain substances that exert oxygen demand. ADL (1984) estimated that produced water discharges for an operation off California could have COD levels of 100-3,000 mg/liter and BOD_5 levels of 300-2,000 mg/liter. The minerals Management Service (1983) presented information that indicated BOD_5 ranged between 370-1,920 mg/l and that COD ranged between 340 - 3,000 mg/l. The presence of oxygen consuming substances was evident in bioassay tests on produced water (Rose and Ward, 1981), most of which had to be aerated to maintain oxygen levels

TABLE 2-29 PRODUCED WATER VOLUMES AND POSSIBLE (ANNUAL) LOADINGS OF PRIORITY POLLUTANTS TO THE MARINE ENVIRONMENT

Facility	Volume[a,b] m^3/day (bbl/day)	Annual Loadings (kg)						
		Benzene	Toluene	Ethylbenzene	Naphthalene	M,P Xylene	2.4 Dimethylphenol	Phenol
Buccaneer Field, Shell Platform[c]	95.3 (600)	194 - 617	91 - 296	7.3 - 37	-	18.3 - 65.7	NA	NA
30 Platforms in EPA Verification Study[d]	21.3 - 23,835 (134 - 150,000)	21.9 - 25,900	14.6 - 17,462	3.65 - 3,749	1.46 - 1,628	NA	1.46 - 1,741	18.3 - 20,385
Average Excluding Central Facilities	637.4 (4,011)	0.365 - 2,825	14.6 - 4,606	1.1 - 1,398	3.65 - 340	NA	ND - 814	14.6 - 4,844
Average including Central Facilities	1,521.8 (9,577)	1.1 - 6,749	32.9 - 10,997	3.65 - 3,340	11 - 807	NA	ND - 1,909	36.5 - 11,560
Trading Bay Facility in[e]	9,851.8 (62,000)	13,304 - 23,375	6,833 - 12,228	1,800 - 4,676[f]	NA		NA	NA

NOTES

a. Volume of produced water at Buccaneer Field during the period of this field study is based on Middleditch (1981, pg. 10).

b. Volume of produced water at Trading Bay Facility, Alaska, is based on Lysyj (1981).

c. Loadings for the Buccaneer Field were estimated by multiplying the estimated discharge volume by the range in concentration reported for produced water from the field.

d. Loadings for the 30 platform study discharges were estimated by multiplying the range in discharge volumes by the average concentrations, and the average discharge volumes by the range in concentrations.

e. Loadings for the Trading Bay Facility were estimated by multiplying the estimated flow by the reported range in concentrations for discharges in Alaskan waters.

f. Concentrations are for a combination of ethylbenzene and xylenes.

above 4 mg/liter. In one series of tests where aeration was not performed, oxygen levels decreased to 0.5-3.2 mg/liter and 1.2-4.0 mg/liter; controls remained above 4 mg/liter.

ADL (1984) also estimated that the BOD inputs associated with projected three and eight platform scenarios in the Santa Barbara Channel were 6,740 and 18,000 metric tons per year, respectively. They compared this to the input from the five major southern California municipal outfalls (264,000 metric tons BOD/year). ADL estimated there could be localized reductions in oxygen near the combined produced water outfall. The presence of oxygen consuming substances in produced water was also reported for North Sea operations.

Based on the BOD data for produced water provided by ADL (1984), e.g., an average BOD of 400 mg/liter with a range of 300 to 2,000 mg/liter, an estimate of total input of BOD in produced waters can be made. Total produced water values for the Gulf of Mexico are available, based on industry sponsored study performed by Walker, Haydel and Associates (1984). Using an estimated total produced water value of 1,551,370 bbl/day for the Gulf of Mexico in 1982, one can calculate an average BOD loading in the Gulf of Mexico from produced water of 36,965 tons with a range of 27,180 to 781,200 metric tons per year.

2.5.2 Added Chemicals

Information on chemicals added to produced water is provided in a report prepared for the American Petroleum Institute by Middleditch (1984). Section 2.7 of that report is reprinted in italics below. Where supplementary information has been incorporated by EPA's technical writers, this is shown in regular type.

Many different chemicals may be used on production platforms as biocides, coagulants, corrosion inhibitors, cleaners, dispersants, emulsion breakers, paraffin control agents, reverse emulsion breakers, and scale inhibitors. Detergents used to clean the platforms will also be found in produced water. The use of chemicals varies from one platform to another, and it is unusual for more than a few of the many available chemicals to be employed on any one platform. JACKSON et al., (1981) has provided information on the chemicals used on ten Louisiana production platforms: Table 2-30 *lists the individual chemicals mentioned in that report, along with information on their compositions obtained from the suppliers. Most of the chemicals are proprietary in nature and many are not composed of individual chemicals with defined structures, so only an indication of their identification or functions can be given.*

Much of the information in this section of the review was provided by interviews with chemical suppliers.

2.5.2.1 Biocides

Sulfate reducing bacteria (such as Desulfovibrio) can convert sulfate ions to sulfide ions, which will corrode metal pipes and storage vessels. Sulfate ions, in turn, are produced from elemental sulfur by the action of sulfur oxidizing bacteria. One method of minimizing this effect is to reduce the bacterial populations by adding biocides to the product stream. These substances, or their degradation products will, therefore, be discharged in the produced water. Two biocides were used in the Buccaneer Field during the first two years of the study performed by MIDDLEDITCH (1981): K-31 (glutaraldehyde) and KC-14

TABLE 2-30

CHEMICALS ADDED TO THE PRODUCED WATER ON PLATFORMS SURVEYED BY JACKSON et al., (1981), WITH ADDITIONAL INFORMATION PROVIDED BY THE MANUFACTURERS OF THE CHEMICALS (MIDDLEDITCH, 1984).

CHAMPION DQ61. Biocide

DOW CORNING 200. Foam inhibitor. Silicone polymer.

EXXON VARSOL. Hydrocarbon solvent.

GREAT SOUTHERN VALVE AND CHEMICAL GS1011. Heavy duty degreaser.

M-CHEM DW-9 RIG WASH. Soap.

METHANOL. Dewatering agent.

NALCO 8AF542. A blend of aluminum salt/polyamides-polyamines in an aqueous solution.

NALCO VISCO 914. Paraffin control agent. Oxyalkylated surfactants in terpene and aromatic solvent.

NALCO VISCO 970. Gas system corrosion inhibitor. A blend of fatty acid amide salts in a hydrocarbon solvent.

NALCO KOAGULAN 3349. Flotation aid. Oxygenated polyamines and inorganic salts.

NALCO VISCO 4400. Demulsifier. A blend of oxyalkylates.

TRETOLITE BR-4050 BROUSSARD. Demulsifier. A solution of polyglycol, oxyalkylated phenol formaldehyde resins, oxyalkylated phenols, and aryl sulfonates in aromatic hydrocarbons and fatty alcohols (C_6-C_8).

TRETOLITE VEZ D-91. Antifoamer. A solution of silicon compounds in aromatic hydrocarbons.

TETROLITE F-17. A solution of aryl sulfonates in aromatic hydrocarbons.

TRETOLITE TOL-FLOTE FR-81. Flotation aid. A solution of polyacrylamides in water and methol.

TABLE 2-30
(Continued)

CHEMICALS ADDED TO THE PRODUCED WATER ON PLATFORMS SURVEYED BY JACKSON et al., (1981), WITH ADDITIONAL INFORMATION PROVIDED BY THE MANUFACTURERS OF THE CHEMICALS (MIDDLEDITCH, 1984).

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TRETOLITE TOL-FLOTE FR-87. Flotation aid. A solution of slats of quaternized amines, an acrylic polymer, a carboxylic acid, and salt in water and methanol.

TRETOLITE TOL-FLOTE FR-88. Flotation aid. A solution of quaternized amines in water.

TRETOLITE TOL-FLOTE FR-98D. Flotation aid. A solution of an acrylic-type polymer, salts of oxyalkylated amines, and salt in water and methanol.

TRETOLITE JW-8206. Flotation aid. A solution of salts of condensed alkanolamines, quaternized amines, and zinc chloride in water and methanol.

TRETOLITE RN-3003. Demulsifier. A solution of oxyalkylated phenol formaldehyde resins in aromatic hydrocarbons.

TRETOLITE RP-34. Demulsifier. A solution of oxyalkylated phenol formaldehyde resins, polyglycols, and acylated polyglycols in aromatic hydrocarbons and methanol.

TRETOLITE RP-79. Demulsifier. A solution of polyglycols in aromatic hydrocarbons.

TRETOLITE RP-101. Demulsifier. A solution of polyglycols, oxyalkylated phenol formaldehyde resins, and oxyalkylated phenols in aromatic hydrocarbons and fatty alcohols.

TRETOLITE RP-2256. Demulsifier. A solution of oxyalkylated phenol formaldehyde resins in aromatic hydrocarbons.

TABLE 2-30
(Continued)

CHEMICALS ADDED TO THE PRODUCED WATER ON PLATFORMS SURVEYED BY JACKSON et al., (1981), WITH ADDITIONAL INFORMATION PROVIDED BY THE MANUFACTURERS OF THE CHEMICALS (MIDDLEDITCH, 1984).

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TRETOLITE RP-2327. Demulsifier. A solution of oxyalkylated phenol formaldehyde resins, aryl sulfonates, and osyalkylated alkanolamines in aromatic hydrocarbons and isopropanol.

TRETOLITE SCALE PREVENTIVE SP-36. Scale inhibitor. A dry powder of sulfamic acid coated with a quaternized amine and an oxyalkylated phenol.

TRETOLITE SCALE PREVENTIVE SP-175. Scale inhibitor. A solution of polyphosphate esters of oxyalkylated polyols and alkanolamines in water and methanol.

TRETOLITE SCALE PREVENTIVE SP-246. Scale inhibitor. A solution of an organic phosphonate in water.

TRETOLITE FLUDEX WF-123. Scale inhibitor. A solution of salts of acylated amines and organic phosphonates in water and methanol.

TRETOLITE FLUDEX WF-75S. Multi-purpose water treatment additive. A solid stick containing polyglycols, quaternized amines, fatty amines, and oxyalkylated phenol formaldehyde resins.

TRETOLITE X-CIDE XC-102. Biocide. An aqueous solution of glutaraldehyde.

TRETOLITE X-CIDE XC-370. Biocide. A solution of oxydiethylenebis (alkyl dimethyl ammonium chloride) in water and methanol.

TIDE. Detergent.

(alkyldimethylbenzyl chloride), both supplied by Champion Chemical Company. A surfactant (Surfatron DQ44) was also employed. The weekly alternation in application of the two biocides was only partially successful in reducing the bacterial populations, so Shell Oil Co. began using Magnacide B (acrolein) during the third year of the study. Acrolein is a highly volatile, toxic, and reactive substance, and residual acrolein in produced water was scavenged by treatment with Magnatreat OS-L (sodium biosulfite) prior to discharge. Acrolein was never detected in produced water samples during this study (MIDDLEDITCH, 1981: ROSE and WARD, 1981). However, Middleditch (1984) notes that it may be released, i.e., the chemical reaction reversed, following discharge.

Other traditional biocides include fatty amines and quaternary ammonium compounds. More modern biocides, which hydrolyze easily and have relatively low fish toxicities, include 2,2-dibromo-3-nitrilopropionamide and chlorinated isothiazolines.

Most biocides are used in concentrations no higher than 20 ppm, and the concentrations in the effluents are usually a few ppm at most. There are, however, little or no quantitative data on biocide concentrations in produced water discharges.

2.5.2.2 Coagulants

These include cationic and anionic substances and quaternary ammonium compounds. Some coagulants contain zinc chloride in concentrations of 5-30 percent. Excessive concentrations of coagulants have an opposite effect from that intended, so treatment with 1-5 ppm is attempted initially, and the concentration may be raised later if the treatment proves to be ineffective. Treatment at the rate of 20 ppm with a formulation containing 30 percent zinc chloride will lead to discharge of 7 ppm of zinc chloride in the effluent.

2.5.2.3 Corrosion Inhibitors

Corrosion inhibitors may contain fatty amines, fatty acid amides, quaternary ammonium compounds, and fatty amine salts. Almost all are cationic in nature. The amines are relatively toxic toward fish, and the surface active agents tend to coat the gills of fish. However, most of the residual corrosion inhibitor is contained in the oil, with much less than 1 ppm remaining in the effluent. (Again, there is little quantitative data on these concentrations.)

2.5.2.4 Cleaners

Detergents used for washing the platforms collect in the separator tanks (so that residual oil can be removed) and will be included in the produced water. Concentrations of these detergents would usually be low.

2.5.2.5 Emulsion Breakers and Dispersants

Emulsion breakers may be nonionic or anionic polymers and include sulfonates and other esters as well as alkylene oxides. Most are oil-soluble, but some are partially soluble in water. The alkylene oxides are more soluble in oil at the elevated temperatures which normally prevail. Low concentrations of ethoxylates and low-molecular-weight acrylates might be employed as dispersants.

2.5.2.6 Paraffin Control Agents

The heavier paraffins can precipitate from the product stream at ambient temperatures. Most control agents are fatty esters, which are oil-soluble. Phenol adducts are also employed.

2.5.2.7 Reverse Emulsion Breakers

See coagulants.

2.5.2.8 Scale Inhibitors

Scale inhibitors include phosphonates, phosphate esters, inorganic phosphates, and acrylic polymers. Typical concentrations in effluents are 5-10 ppm. These substances are biodegradable and, accordingly, will elevate the BOD of the produced water.

2.5.3 Effects of Platform Age on Pollutant Concentrations in Produced Waters

It has been suggested that produced water pollutant concentrations may change through time at a particular well. For example, since water content (or water cut) of the produced fluid generally increases as the well is depleted, the concentration of organic pollutants might decrease with increasing well age. To test this possibility, data from the 30 platform EPA Verification Survey (EPA, 1982) were evaluated to examine how pollutant concentrations in treated produced water differed with the age of the production operation. Three pollutants--benzene, phenol, and zinc--were selected for this analysis because they were among the most common pollutants in the produced water discharges. Concentrations of these chemicals in produced waters were compared among platforms that differed in age as well as platforms with different water cuts (sometimes an indicator of reservoir depletion). The results of this analysis did not demonstrate any strong correlations of chemical concentrations with indicators of platform/production age.

2.6 OTHER DISCHARGES

Other discharges from offshore oil and gas operations include deck drainage, sanitary, and domestic wastes, and other minor waste sources such as food scraps, discharges from compressor drains, cooling and heating circuits, desalinization units, ballast from service/supply boats, cement unit deck drains, BOP fluids, and produced sands. Most of these are not well covered in the literature. Minimum and maximum discharge rate estimates for some of these sources are shown in Table 2-31.

2.6.1 Composition and Discharge of Deck Drainage

Oil is the primary pollutant in deck drainage, although detergent used in deck and equipment washing is also of concern. During well completion, spillage of drilling fluids may occur. Various acids are also used during workover operations and contribute to deck drainage, but generally these are neutralized prior to disposal.

TABLE 2-31 OTHER OFFSHORE DRILLING RIG DISCHARGES

Discharge name and parameters	Average Flow Rate			
	Minimum		Maximum	
	gpd	m^3/d	gpd	m^3/d
Contaminated deck drainage (work area drainage) average flow rate	800	3.2	14,000	53.0
Sanitary waste discharge average flow rate (saltwater used)	1,500	5.7	5,000	18.9
Kitchen & shower discharge (grey water) average flow rate	1,500	5.7	8,000	30.3
Water distillation discharge average flow rate (saltwater brine)	5,000	18.9	36,000	136.3
Clean deck drainage (rainwater and washwater) average flow rate	2,800	10.6	13,200	50.0
BOP (blow out prevention) systems) fluid average flow rate	10	0.1	500	1.9
Boiler blowdowns average flow rate	--	--	200	0.1
Fire water systems average flow rate	-------SYSTEMS TEST ONLY-------			
Cooling water (power generation system) average flow rate	400,000	1,515	5.2/MGD	19,690
Delta temperature (discharge °F - inlet °F)	--	--	5°F	--
Ballast water average flow rate (with no additives)	3,000	11.4	26,000	98.4
Cementing unit & washdown drains average flow rate	20	0.1	500	1.9

Source: from DOI, 1982a.

A typical platform-supported rig is equipped with pans to collect deck and drilling floor drainage, which are gravity separated into waste material and liquid effluent. Waste materials are recovered in a sump tank, and either treated prior to disposal, used in the drilling mud system, or transported to shore. The liquid effluent consists primarily of wash water and rain water, and is discharged overboard. A typical rig discharges between 2,800 and 13,200 gallons of clean deck drainage, and between 800 to 14,000 gallons of contaminated deck drainage (from the work area) daily (DOI, 1982a).

2.6.2 Discharge of Sanitary and Domestic Wastes

The largest volumes of sanitary and domestic wastes are generated during the drilling phase of oil and gas production when manpower needs are highest. Domestic wastes, primarily kitchen, laundry, and showering water ("grey water"), receive little or no treatment before discharge. These waste flows can range as high as 8,000 gallons and 5,000 gallons per platform per day for domestic and sanitary waste, respectively (DOI, 1982a). Sanitary wastes are estimated to contribute approximately 0.2 pounds per person per day of BOD loading (Frazier et al., 1977), and are treated prior to disposal. At peak occupancy, a drilling rig might support between 12 and 80 persons.

3.0 ENVIRONMENTAL FATE

3.1 SUMMARY

3.1.1 Drilling Fluids and Drill Cuttings

Field studies and models of the behavior of drilling fluids and cuttings discharged to the marine environment have focused on several aspects of their fate. Among these aspects are: the transport of discharged materials in the water column, both for particulate and soluble components; deposition on the seafloor; and considerations of benthic short- and long-term fate.

Discharged drilling fluids generally separate into two plumes. Most of the discharged material (~90 percent by weight) descends through the water column with the lower plume. It is this plume that contributes most directly, and in greatest quantity, to discharged materials deposited on the seafloor. The upper plume, which is usually present in the upper 10 to 20 m, contains the remaining material. Generally, the lower plume, and its deposition of particulates on the seafloor, has been considered most important to possible impacts on the seafloor biota from discharge plumes. The upper plume has received the most attention with regard to possible water column impacts.

Field studies of suspended solids dispersion have sampled the upper plume virtually exclusively. Results of four such studies (two in the Gulf of Mexico, one off southern California, one in the Atlantic) have been integrated and described by an empirically-derived multiple regression analysis that estimates dispersion of solids, as a function of time and discharge rate. This relationship was developed at an EPA-sponsored Adaptive Environmental Assessment (AEA) workshop. Predictions based on this relationship, for a current speed of 15 cm/sec, indicate that dispersion in the upper plume, as measured by suspended solids, will approximate 10^4 within 100 m, 10^5 within 500 m, and 10^6 within 2,000 m.

Because drilling fluids contain both particulate and soluble components, and because particulates have an additional mode of dispersion that does not apply to soluble components (i.e., gravitational settling, which takes solids out of the water column and transfers them to the sediment), several estimates of soluble component dilution also have been made. Generally, it appears that dilution of soluble material in the upper plume may proceed at one-half to one-tenth that of dispersion particulates in the upper plume. Although these estimates are reasonably consistent, this observation must be somewhat tempered, however, because of the difficulties involved in assessing interactions between soluble tracers and drilling fluid components, such as fine particulates.

Dilution of drilling fluids in the water column beneath ice has been examined in the Beaufort Sea. Results suggested that nearfield dilution (100- to 1,000-fold) was 1-2 orders of magnitude less than in open water situations. However, at dilution ratios of 10^4 to 10^6, the dilution under ice appeared to approach that in open water. Sampling problems encountered in this study may have resulted in an overestimation of far-field dispersion. Therefore, these data must be interpreted very cautiously.

Drilling fluid components in a lower plume that reaches the seafloor may be transported as a turbulent bottom plume. Solids will continue to settle out while soluble components will be diluted with distance. Such plumes have been observed for dredged material disposal but no observations of such plumes for drilling fluids have been attempted. Data on the short-term fate of drilling discharges associated with the lower plume appears largely to address the initial deposition of the material on the seafloor. The lack of information on the behavior of the lower plume generally should not be as critical for exploratory operations. However, because of the continued, long-term input associated with development operations, this data gap represents a concern for potential long-term impacts.

A model has been developed by the Offshore Operators Committee (OOC) for predicting the behavior of solid and soluble components of the lower plume. This model appears to provide a good physical representation of the fate of these materials, within limits. The model has performed well when compared to dynamic tank tests. However, field verification of the model has not been completed. A verification study currently is in progress. Thus, the present state of knowledge of the behavior of drilling fluid plumes is that:

1. the upper plume, which comprises some 10 percent of the material discharged and generally represents a minor component for benthic impacts, has adequate field data to develop empirical predictions of dispersion but has not been physically modeled;
2. the lower plume, which comprises some 90 percent of the material discharged and represents a major component for benthic impacts, has a well-developed physical model but has no sampling data to assess the accuracy of model predictions.

Much of the discharged drilling muds and cuttings will initially reach the seafloor within a few hundred meters from the drilling platform. In situations where a number of wells are being drilled from a development platform, a pile of cuttings (on the order of meters in thickness) could develop around the platform and extend out to a few hundred meters. The thickness of the cuttings pile would decrease with distance from the platform. Finer materials, (e.g., barite and clays) associated with the cuttings, may extend further out from the platform. For a single exploratory well drilled in the mid-Atlantic, elevated clay levels, believed to be associated with cuttings, extended out to approximately 800 m from the well.

The subsequent fate of this deposited material will depend primarily on the physical processes that resuspend and transport particulates or entrain them into the sediments. Biological or chemical factors could also be important in stabilizing or mobilizing the material on the seafloor (e.g., through covalent binding of sediments or bioturbation).

Analyses of sediment barium and trace metal concentrations have been used to examine nearfield fate of drilling fluids on the seafloor, e.g., the rate of dispersion of sedimented material. If high concentrations of barium are persistently found near a well site, this finding suggests it is in a lower energy area, which favors deposition. If elevated levels cannot be found, even soon after drilling, then this finding suggests a higher energy environment, where resuspension and sediment transport were promoted.

At present, the area-wide large-scale distribution of drilling discharges is difficult to predict. However, it can be surmised that a number of drilling operations associated with the development of a particular field could contribute to a general regional increase of drilling-related materials on the seafloor (many of these, perhaps not easily demonstrable, because of natural, sampling, and analytical variability).

A power-law regression analysis was developed to relate average barium levels to distance from the discharge source. These equations described well the distance-dependent decrease in sediment barium levels obtained in four field studies. A multivariate analysis was used to estimate average sediment barium levels with respect to distance and number of wells. At locations of approximately 100 m to 30,000 m from a nine-well platform, this analysis suggested that sediment barium data collected early in the development phase of an operation may provide accurate predictions of sediment barium levels later in the operation.

Two attempts have been made to estimate spatial distribution of discharged material from a two-well operation in the Gulf of Mexico. One industry sponsored analysis indicated that 49 percent of discharged barium had been dispersed beyond a radius of 1,250 m from the platform. Another analysis of these data indicated that 78 percent of the barium was located within a 1,000 m radius, and essentially all of the barium (calculated as 111 percent) was located within 1,250 m.

Data from exploratory drilling operations have been used to examine deposition of metals resulting from drilling operations. These indicate that several metals are deposited, in a distance-dependent manner, around platforms, including cadmium, chromium, lead, mercury, nickel, vanadium, and zinc.

Chemical and biological transport of drilling fluids is poorly described. Much must be gleaned from general principles and studies of other, related materials. Several broad findings are suggested, but the data for a quantitative assessment of their importance are lacking. Chemical transport will most likely arise from oxidation/reduction reactions that occur in sediments. Changes in redox potentials will effect the speciation and physical distribution (i.e., sorption-desorption reactions) of drilling mud constituents.

Bioaccumulation of a number of metals from exposure to muds and mud components has been demonstrated in the laboratory and in the field. Short-term laboratory experiments and field exposures indicate that tissue enrichment factors were generally less than an order of magnitude, with the exception of barium and chromium. However, target organ analyses were scant and improper test phases were often used. Also, long-term exposures, which are particularly relevant to assessing impacts of development operations, have been studied just recently. Thus, a bioaccumulation potential for these discharges has been qualitatively demonstrated, but cannot be assessed quantitatively at this time.

Bioaccumulation of organics from drilling fluids, in particular those associated with (diesel or mineral) oils added as lubricants, has not been studied. However, such studies of these oils themselves or their component substances indicate that a variety of their toxic constituents can be bioaccumulated. Again, however, only a qualitative conclusion may be reached.

3.1.2 Produced Water

The major processes affecting the fate of discharged produced water and associated chemicals include dispersion and advection, volatilization, and adsorption/sedimentation. Concentrations of volatile liquid hydrocarbons discharged with produced water at the Buccaneer Field were reduced on the order of 10^4-10^5 within 100 m from the platform, but generally elevated levels were observed 3.5 km away. The Buccaneer Field platform (600 bbl/day) is at the lower end of discharge volumes reported for the EPA verification study (134 bbl/day-150,000 bbl/day).

Hydrocarbons that become associated with sedimentary particles, either through water column interaction, settling to the seafloor, or through bottom impact of the discharge plume, can accumulate around production platforms. This was particularly evident in the Trinity Bay Study. Concentrations of naphthalenes in the sediment were enriched compared to effluent levels (21 mg/kg sediment versus 1.62 mg/liter in the effluent). Also, levels of naphthalenes were elevated in the immediate vicinity of the discharge with a subsurface concentration maximum in the sediment. Subsequent fate of petroleum hydrocarbons associated with sediments will depend on the processes involved in resuspending and transporting the sediments, desorption processes and biological processes. Because produced waters provide a continuing input of light aromatic hydrocarbons over the life of a field (generally 10 to 30+ years), there is the potential for these chemicals to accumulate in sediments. This differs from oil spill situations wherein the chemicals are rapidly lost and the sediments generally exhibit a decline of lighter aromatics with time.

To evaluate the impacts of produced water discharges in shallow water, EPA employed a modified PLUME model. A series of model runs were conducted to assess the potential for benthic impacts from produced water discharges. Discharge scenarios were developed for average discharge volumes for various projected platform sizes, which were based on estimates provided by the Eastern Research Group, Inc.

Because of the substantially increased possibility of sediment accumulation of pollutants resulting from bottom impact of the discharge plume, an analysis was conducted to assess the potential for bottom impact. Results of this analysis show that bottom impact is projected for water depths approximately 20 meters or less. Thus, bottom impact is projected for 12-well platforms or larger in the territorial seas off of Texas and Louisiana. Bottom impact is projected for larger platforms (40-58 wells) in Federal waters offshore Texas and Louisiana.

3.2 INTRODUCTION

Drilling fluids contain quantities of coarse material, fine material, dissolved solids, and free liquids. Upon discharge, this mixture separates rapidly. An upper plume is formed, probably from shear forces and local turbulent flow at the discharge pipe. This plume will migrate to its level of neutral buoyancy; particulates will slowly settle to the bottom. This plume is advected with prevailing currents. The fine solids settle at a rate depending on aggregate particle size, which therefore, is very dependent on flocculation. The upper plume contains about five to seven percent, by weight, of the total drilling fluid discharge (Ayers et al., 1980b).

A lower plume contains the majority of discharged materials. Coarser materials fall rapidly to the bottom out of the lower plume, with a transit time so brief that the influence of current is minimal. Ayers et al., (1980b) found lower plume components deposited on the bottom within a few meters of the discharge point. If water depths are great enough to prevent bottom impact, the lower plume also will reach its level of neutral buoyancy. Fine mud particulates will be advected with ambient current flow, similar to their behavior in the upper plume.

Both upper and lower plumes are affected by three kinds of transport processes or pathways: physical, chemical, and biological. Physical transport processes affect concentrations of discharge components in the water column through dilution, dispersion, and settling. Chemical and biological processes are more significant for changes produced in the structure and/or speciation of materials that affect their bioavailability and toxicity.

- Physical processes include currents, mixing, settling, and diffusion. These processes include current velocity and direction, tidal regime, kinetic energy regime, and such receiving water characteristics as density and stratification. Physical processes are the best understood of the three transport pathways.

- Chemical processes include the dissolution of substances in seawater, particle flocculation, complexing of compounds that may remove them from the water column, redox/ionic changes, and adsorption of dissolved pollutants on solids.

- Biological processes include bioaccumulation in soft or hard tissues, fecal agglomeration and settling of materials, and physical reworking to mix solids into the sediment (bioturbation).

3.3 PHYSICAL TRANSPORT PROCESSES

3.3.1 Drilling Fluids

Environmental pollutant concentrations resulting from offshore platform discharges are influenced by several factors related to the discharge and the medium into which it is released. Discharge related factors include the solids content of the effluent, distribution of particle sizes and their settling rates, effluent chemical composition, discharge rates and duration, and density.

Environmental factors that affect dispersion and transport of discharged material include velocity, direction, and variability of currents, tidal influences, wave action, wind regime, topography of the ocean bottom, bottom currents, and turbulence caused by the platform wake. These factors influence dispersion of effluents in the water column, and resuspension and transport of solids settled on the seafloor. Areas of high hydrodynamic energy will disperse discharges more rapidly than less energetic areas.

The direction of the current determines the predominant location of potential impacts, while current velocity influences the extent of area affected. Velocity and boundary conditions also affect mixing because turbulence increases with current speed and proximity to the seafloor. Current velocity and turbulence can vary markedly with location/site characteristics and affect the movement and concentration of suspended matter, and entrainment/resuspension/advection of sedimented matter.

3.3.1.1 Study Descriptions

Data from four offshore oil environmental studies (in Georges Bank, Lower Cook Inlet, Tanner Bank, and the Mid-Atlantic) illustrate variations in current regimes. At the Georges Bank drilling location, flow varies seasonally (Houghton et al., 1981). Flow follows a partially closed, clockwise gyre, averaging 10 cm/sec (0.33 ft/sec). A diffusion model estimate that the residence time of a water parcel would be two to three months during the summer and less than one month during the winter (Butman et al., 1980 as in Houghton et al., 1981). Strong currents at the periphery of the gyre would dilute a plume and transport it out of the area. However, entrainment of a plume in the central water portion, due to the gyre, could prolong exposures for organisms.

At Lower Cook Inlet, tidal currents dominate the net circulation current (ARCO, 1978 as in Petrazzuolo, 1981). These tidally driven currents switch directions every six hours, and transport plots indicate little net movement. Representative current velocities and directions at three depths are shown for one site in Table 3-1 (Houghton et al., 1981). Considerable cross-current turbulence is also produced in Lower Cook Inlet throughout the water column during ebb and flood tides, increasing the mixing action to which the discharges are subjected.

TABLE 3-1 LOWER COOK INLET CURRENT
VELOCITIES AND DIRECTION
(Houghton et al., 1981)

	Flood tide		Ebb tide	
Current meter depth (m)	Speed cm/sec (knots)	Avg. direction, degrees (true)	Speed cm/sec (knots)	Avg. direction, degrees (true)
14	77.6 (1.5)	35	102.88 (2.0)	225
31	61.73 (1.2)	35	66.87 (1.3)	220
52	51.44 (1.0)	15	41.15 (0.8)	185

Tanner Bank is an example of a high energy regime affected by numerous surges and shifting currents, but with a predominant surface and mid-depth flow to one direction, the southeast (Ecomar, 1978 as in Petrazzuolo, 1981). Net surface water movements were to the southeast and ranged from 0 to 67 cm/sec (2.20 ft/sec), averaging 22.6 cm/sec (0.74 ft/sec). Net mid-depth currents were to the east-southeast at an average 20.6 cm/sec (0.68 ft/sec). Near-bottom currents were measured at 61 m in 63 m of water and averaged 24 cm/sec (0.79 ft/sec) with a north-northwesterly flow. Wave-induced orbital current patterns occurred intermittently at all depths at intervals of about one day.

The Mid-Atlantic outer continental shelf near the continental break east of Atlantic City, New Jersey, is an example of a low-energy regime. The area is characterized by a strong diurnal tide superimposed on a mean south or southwesterly flow (EG&G, 1982). Bottom currents, which play an important role in sediment resuspension and transport, flowed to the southwest 35 percent of the time, and to the southeast, northwest, and northeast 28, 25, and 12 percent of the time, respectively. Bottom currents were less than 10 cm/sec 62 percent of the time and less than 25 cm/sec for 95 percent of the time.

In addition to current velocity, Houghton et al., (1980 and 1981) indicate that turbulence, induced by submerged portions of the drilling platform, may significantly contribute to current effects on the dispersion of the muds. They attribute increased dispersion of discharged materials, resulting from transit through the submerged structure of a Cook Inlet platform, to rig-induced turbulence. In their 1981 paper, they concluded this turbulence will be significant if current speeds are 5 to 10 cm/sec (0.16 to 0.32 ft/sec) or greater. However, this wake-effect has not been systematically studied at other locations. Ray and Meek (1980), for example, observed little change in plume dilution with velocity variations between 2 and 45 cm/sec (0.076 and 1.48 ft/sec) at Tanner Bank.

3.3.1.2 Physical Transport Processes Affecting the Upper Plume

The materials contained in the upper plume may be subjected to immediate wake-induced turbulence, and then are influenced by oceanic turbulent dispersion processes. These materials are transported at the speed and direction of prevailing currents. Sinking rates of solids in the upper plume will largely depend on four factors:

- discharged material properties
- receiving water characteristics
- currents and turbulence
- flocculation and agglomeration

Physical properties of the discharged materials affect mixing and sedimentation. For suspended clay particulates, particle size and both physical and biological flocculation will determine settling rate. While oil exhibits little tendency to sink, it has displayed the ability to flocculate clay particles and to adsorb to particulates and sink with them to the bottom (Middleditch, 1980).

One of the major receiving water characteristics influencing plume behavior is density structure and stratification. Density stratification can contribute to the dissipation of dynamic forces in the dynamic collapse phase of plume behavior, and represents the point at which passive diffusion and settling of the individual particles become the predominant dispersive mechanisms. Density stratification may concentrate certain components along the pycnocline. If flocculation produces particles large enough to overcome the barrier, settling will continue. Also, if density stratification is weak or the pycnocline is above the discharge point, it may not affect plume behavior.

Ecomar (1978), as reported in Houghton et al., (1981), noted that upper plumes in the Gulf of Mexico followed major pycnoclines in the receiving water. A similar finding has been observed by Trefry et al. (1981) who traced barium levels along pycnoclines. This type of transport is a potential concern because sensitive life stages of planktonic, nektonic, and benthic organisms may collect along the pycnocline. Ayers et al. (1980b) observed that the bottom of the upper plume followed a major pycnocline after drilling fluid discharges at rates of 275 bbl/hr and 1,000 bbl/hr in the Gulf of Mexico.

Flocculation and agglomeration affect plume behavior by increasing sedimentation rates as larger particles are formed. Flocculation is enhanced in salt or brackish waters due to increased cohesion of clay particles (Meade, 1972). Agglomeration also results in the formation of larger particles from a number of smaller ones through the excretion of fecal pellets by filter-feeding organisms.

The extent to which discharges are dispersed can be estimated using dispersion ratios derived from measurements at several drilling operations. These ratios are calculated as:

$$\text{Dispersion Ratio} = \frac{\text{suspended solids concentration of discharged fluid}}{\text{suspended solids concentration in samples}}$$

Dispersion ratios for drilling fluid discharges sampled in upper plumes have been calculated, based on data from Tanner Bank, the Gulf of Mexico, and the Mid-Atlantic (Petrazzuolo 1981; 1983a). Dispersion data from Lower Cook Inlet and the Beaufort Sea were treated separately because the measured tracer, the current structures, and bathymetry were substantially different from these other OCS study sites. Results are presented in Table 3-2. These data are graphically displayed in Figure 3-1; in Figure 3-2 the aggregate regression line has been drawn. Current-normalized estimates of dispersion in each of these field studies and from a multiple regression (dispersion vs. transport time and discharge rate) of the combined data (Auble et al., 1982) are given in Table 3-3.

Rearranged in Table 3-4 are the data from Table 3-2 and 3-3 to show the generalized distance plumes must travel to achieve

TABLE 3-2 UPPER PLUME DISPERSION RATIOS OF WHOLE DRILLING FLUIDS* (From Petrazzuolo 1983a)

	OCS Study Site (Discharge Rate, bbl/hr)						
Distance, m	TB** (12.8)	GM (57)	GM (275)	MA (275)	MA (500)	TB (750)	GM (1000)
5	-	-	-	5,000	3,100	-	-
15	-	-	-	2,300	9,600	-	-
45	-	-	42,100	-	-	-	1,675
74	-	-	-	-	-	9,900	-
81	96,699	-	-	66,100	-	-	-
100	-	-	-	-	50,000	-	-
145	-	-	168,000	-	-	-	-
151	145,000	-	-	-	-	-	-
200	-	490,000	-	79,300	54,000	-	-
248	191,000	-	-	-	-	-	-
350	-	-	-	-	250,000	-	-
370	-	-	1,190,000	-	-	-	59,400
400	189,000	-	-	-	-	-	-
500	-	-	-	-	-	61,900	-
600		-		694,000		-	-
625		-		-		227,000	-
700		-		214,000		-	-
777		-		-		-	349,000
800		2,250,000		-		52,900	-
878		-		-		-	1,190,000
957		-		-		-	1,723,000
1000		-		-		444,000	-
1470		-					650,000
1550							1,300,000
1600	-	3,600,000	-	-	-	-	-

* Dispersion ratios calculated as: $\dfrac{\text{(suspended solids in discharged fluid)}}{\text{(suspended solids in the sample)}}$

** Abbreviations: TB (Tanner Bank); GM (Gulf of Mexico); MA (Mid-Atlantic)
Reference: Tanner Bank (Shell Oil Company 1978b)
Gulf of Mexico (Ayers et al., 1980b; Trefry et al., 1981)
Mid-Atlantic (Ayers et al., 1980a)

Figure 3–1
Dispersion Ratios of Whole Drilling Fluids

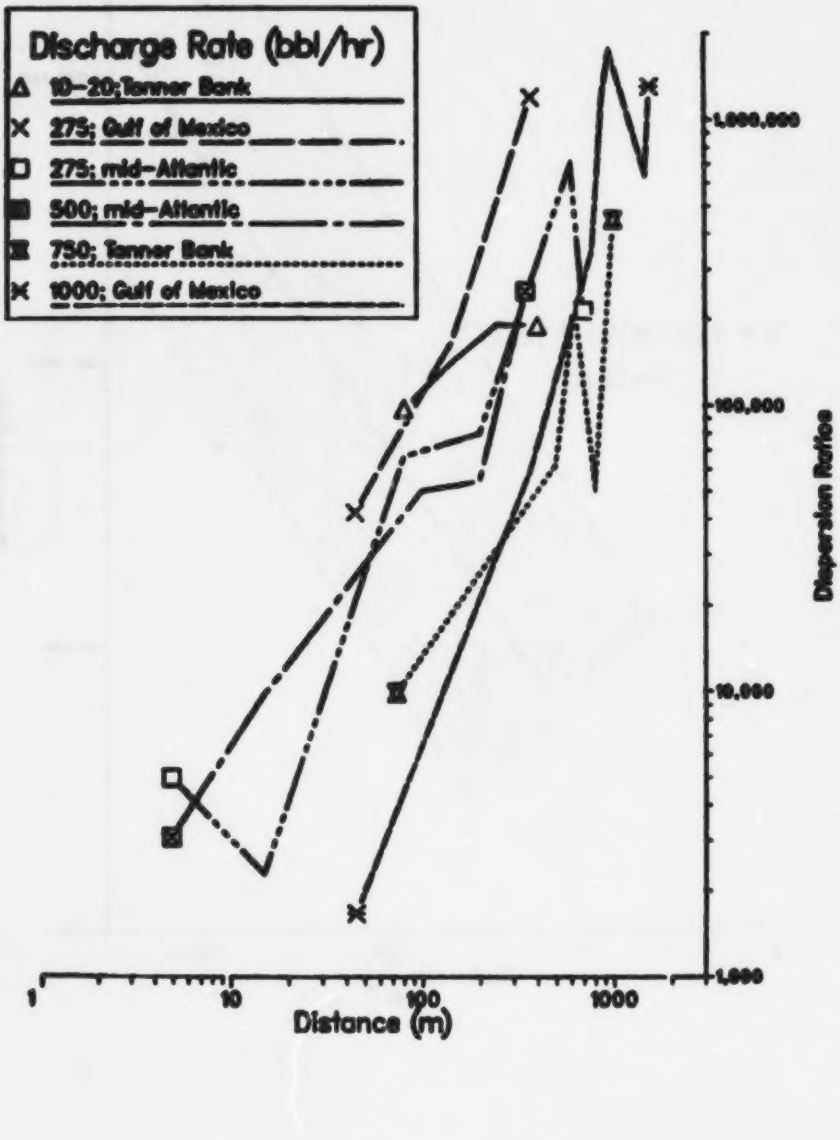


Figure 3-2
Regression Plot of Whole Fluid Dispersion Ratios and 90% Prediction Bands

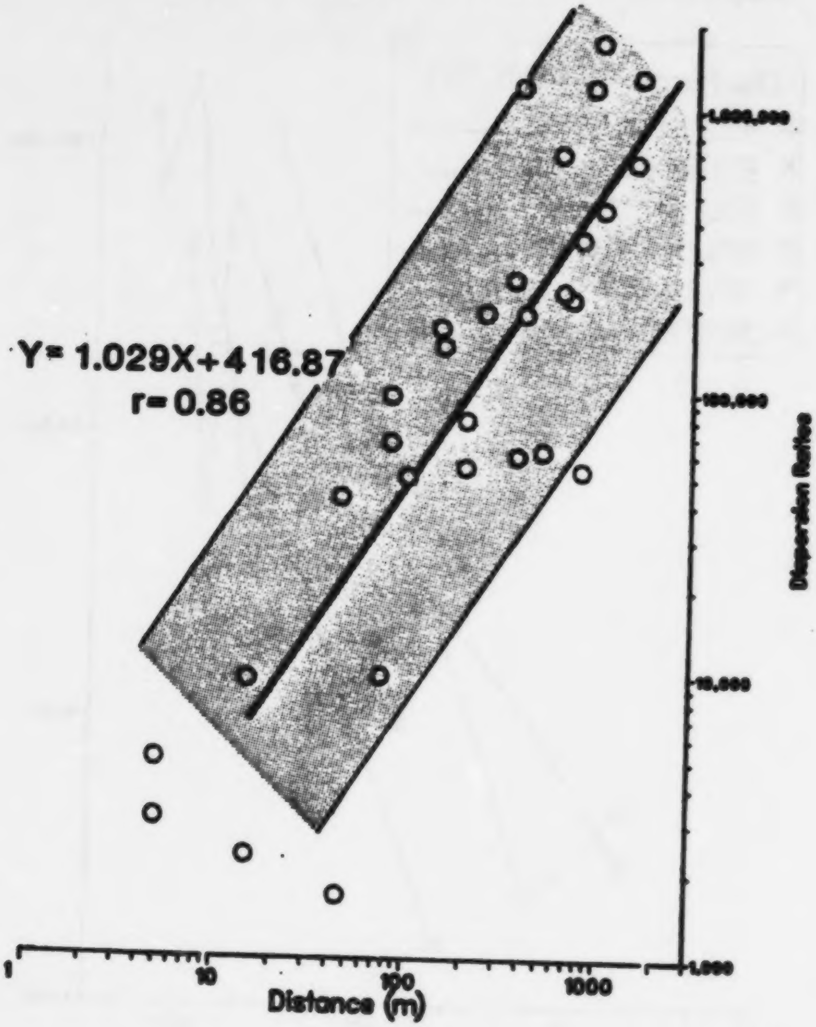


TABLE 3-3 NORMALIZED ESTIMATES OF DISTANCES TO DISPERSION RATIOS OF 10^4, 10^5, AND 10^6 AT CURRENT SPEEDS OF 5, 10, AND 15 cm/sec*

OCS Study Site (Discharge Rate)	Dispersion Ratio				Dispersion Ratio				Disperion Ratio			
		$D_R = 10^4$				$D_R = 10^5$				$D_R = 10^6$		
	t_T (min)	5 (cm/sec)	10 (cm/sec)	15 (cm/sec)	t_T (min)	5 (cm/sec)	10 (cm/sec)	15 (cm/sec)	t_T (min)	5 (cm/sec)	10 (cm/sec)	15 (cm/sec)
TB (12.8)	0.955	2.87	5.73	14.3	9.45	28.4	56.7	85.1	93.6	281	562	842
GM (57)	0.103	0.32	0.62	0.93	1.52	4.56	9.13	13.7	22.5	67.4	135	202
GM (275)	1.69	5.07	10.1	15.2	7.33	22.0	44.0	66.0	31.8	95.4	191	286
MA (275)	1.23	3.69	7.38	11.1	11.9	35.7	71.4	107	112	336	672	1008
MA (500)	1.37	4.11	8.22	12.3	16.5	49.5	99	149	199	597	1194	1791
TB (750)	8.67	26.0	52.0	78.0	44.8	134	269	403	232	696	1392	2088
GM (1000)	11.9	35.7	71.4	107	38.9	117	233	350	127	381	762	1143
EPA/AEA (12.8)	0.891	2.67	5.34	8.02	7.22	21.7	43.3	65.0	58.6	176	351	527
(57)	1.44	4.33	8.66	13.0	11.7	35.1	70.2	105	94.9	285	569	854
(275)	2.41	7.22	14.5	21.7	19.5	58.6	117	176	158	475	948	1420
(500)	2.92	8.77	17.6	26.3	23.7	71.1	142	213	192	577	1155	1730
(750)	3.33	10.0	20.0	30.0	27.0	81.1	162	243	219	658	1315	1975
(1000)	3.66	11.0	22.0	32.9	29.7	89.0	178	267	241	722	1445	2165

* References: From Petrazzuolo, 1983a, based on analyses presented in Auble et al., (1982).

TABLE 3-4 GENERALIZED DISTANCES REQUIRED TO ACHIEVE SPECIFIED LEVELS OF SUSPENDED SOLIDS DISPERSION IN THE UPPER PLUME FOR WHOLE DRILLING FLUIDS AT FIXED CURRENT SPEEDS

Dispersion Criterion	Distance Required (m) (Current Speed, cm/sec) 5	10	15
10^4	35	75	100
10^5	150	300	500
5×10^5	300	700	1000
10^6	700	1500	2000

From Petrazzuolo (1983a).

dispersion ratios of 10,000:1, 100,000:1, 500,000:1, and 1,000,000:1, respectively. From these data, Petrazzuolo (1983a) estimated, for current speeds up to 15 cm/sec, that 10,000:1 dispersions are reached in 100 m (328 ft), 100,000:1 dispersions within 500 m (1,640 ft), 500,000:1 dispersions are attained within 1,000 m (3,280 ft) and 1,000,000:1 dispersions are attained within 2,000 m (6,380 ft).

Most studies of upper plume behavior have measured particulate components and paid less attention to the liquid and dissolved materials present. Presumably, these latter components are subject to the same physical transport processes, with the exclusion of settling, as particulate matter. Studies suggest that suspended solids in the upper plume may undergo a higher dispersion rate than dissolved components.

Houghton et al., (1980) measured upper plume transport using a soluble, fluorescent dye (fluorescein), in Lower Cook Inlet, where the currents are 41 to 103 cm/sec. They found that the plume never sank below 23 m (75 ft), while water depth at the site was 63 m (207 ft). Ayers et al., (1980b) estimated upper plume volume from transmissometry data, in the Gulf of Mexico, and found that a 275 bbl/hr drilling fluid discharge exhibited a dilution ratio of 32,000:1 after 60 minutes and a 1,000 bbl/hr discharge showed a dilution ratio of 14,500:1 after 62 minutes. Dispersion ratios for suspended solids at these distances would be approximately one to two orders of magnitude greater than for soluble components.

Petrazzuolo (1983a) analyzed estimates of "soluble" tracers from the Cook Inlet data and from radiotracer data offshore of southern California. The Cook Inlet data suggested that dilution rates may be comparable to or at a rate approximately half that of dispersion (based on generalized estimates of distances to specified levels of dispersion; Table 3-5). These correlations may be confounded by dye-clay interactions, rendering this comparison more similar than would a true "soluble" component. The radiotracer data indicated that dilution could be 4-10 times less than dispersion (Table 3-6), based on dispersion/dilution estimates at specified distances. However, these data were obtained only from samples taken in the very near field (<100 m).

3.3.1.3 Physical Transport Processes Affecting the Lower Plume

The physical transport processes affecting the lower plume differ somewhat from those influencing the upper plume. The lower plume appears to have a component, comprised of coarser material, that settles rapidly to the bottom regardless of current velocity. This rapid settling is most pronounced during high-rate bulk discharges, with their high downward momentums, and in shallow water, because these conditions tend to result in the plume reaching the bottom. At Tanner Bank, the lower plume was relatively unaffected by average currents of 21 cm/sec (0.69 ft/sec) and bottom surges up to 36 cm/sec (1.18 ft/sec) (Ecomar, 1978).

The amount of fine solids settling to the bottom from the lower plume depends on collision and cohesion of clay particles, which in turn depends on suspended material

TABLE 3-5 ESTIMATES OF DISTANCES REQUIRED TO ACHIEVE SPECIFIED LEVELS OF DISPERSIONS OF A SOLUBLE DRILLING FLUID TRACER AT FIXED CURRENT SPEEDS*

Dispersion Criterion	Distance Required (m)		
	(Current Speed, cm/sec)		
	5	10	15
10^4	10-17	19-34	29-51
10^5	80-146	160-291	240-437
5×10^5	355-657	709-1,313	1,063-1,970
10^6	673-1,256	1,345-2,512	2,018-3,768

*Adapted from Atlantic Richfield (1978); Petrazzuolo (1983a).

Ranges in distances represent discharge rates of 21 to 1,200 bbl/hr.

TABLE 3-6 COMPARISON OF RADIOTRACER DISPERSION VERSUS SUSPENDED SOLIDS DISPERSION AND RHODAMINE-WT DISPERSION[a]

Effluent	Distance (m)	Transport time (min)	TB (10.0) (^3H; ^{46}Sc)	TB (12.8) (TSS)	EPA/AEA (TSS)
Drilling Fluid (HTO)	0.31	0.245	3,130	2,570	2,635
Drill Cuttings (HTO)	0.31	0.06	940	640	571
	77	15.6	23,500	163,644	254,822
Drilling Fluid (^{46}Sc)	3.8	3.07	11,100	32,204	42,657

a. Adapted from Shell Oil Co. (1978b), Auble et al., (1982); in Petrazzuolo (1983a).

Abbreviations:

TB - Tanner Bank; (values in parenthesis indicate discharge rate in bbl/hr);
(TSS) - total suspended solids;
(HTO) - tritiated water.

concentration, salinity, and the cohesive quality of the material. Fine particles tend to flocculate more readily than larger particles. Houghton et al., (1981) cites earlier work by Drake (1976), which concluded that physical-chemical flocculation can increase settling rates an order of magnitude over rates for individual fine particles. Presently, there are no water column sampling data from the lower plume. Its dynamics must be inferred from limited sediment trap data and from models of plume behavior (Brandsma et al., 1980; Offshore Operators Committee, 1984).

Biological processes have been shown to increase settling rates for fine particles, which presumably could affect drilling discharges. Filter feeding plankton ingest particles ranging from 1 to 50 µm in diameter, and excrete them in fecal pellets ranging from 30 to 3,000 µm in size (Haven and Morales-Alamo, 1972, as in Houghton et al., 1981). Copepods have been cited as playing an important role in biologically-induced fine particle agglomeration by Manheim et al., (1970), also as reported in Houghton et al., (1981).

3.3.1.4 Seafloor Sedimentation

Houghton et al., (1981) produced an idealized pattern for sedimentation around an offshore platform located in a tidal regime (Figure 3-3). Zero net current was assumed. The area of impact may have been overestimated from the true field case because no initial downward motion was assumed, which provides for a longer settling time and greater plume dispersion. The result was an elliptical pattern, with the coarse fraction

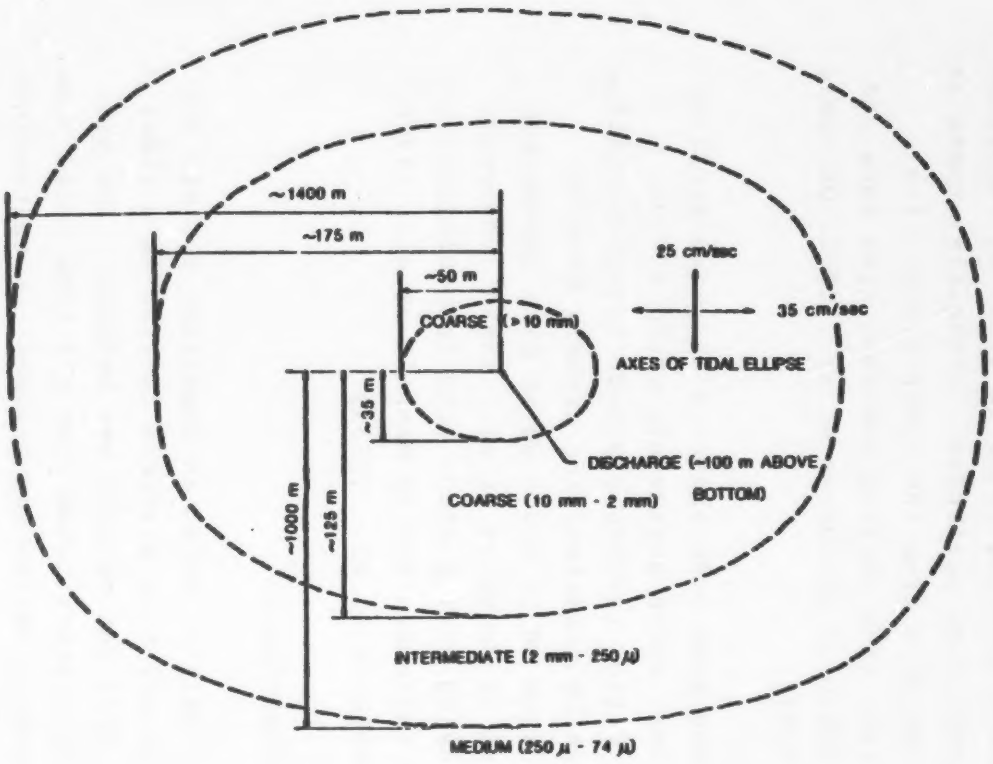


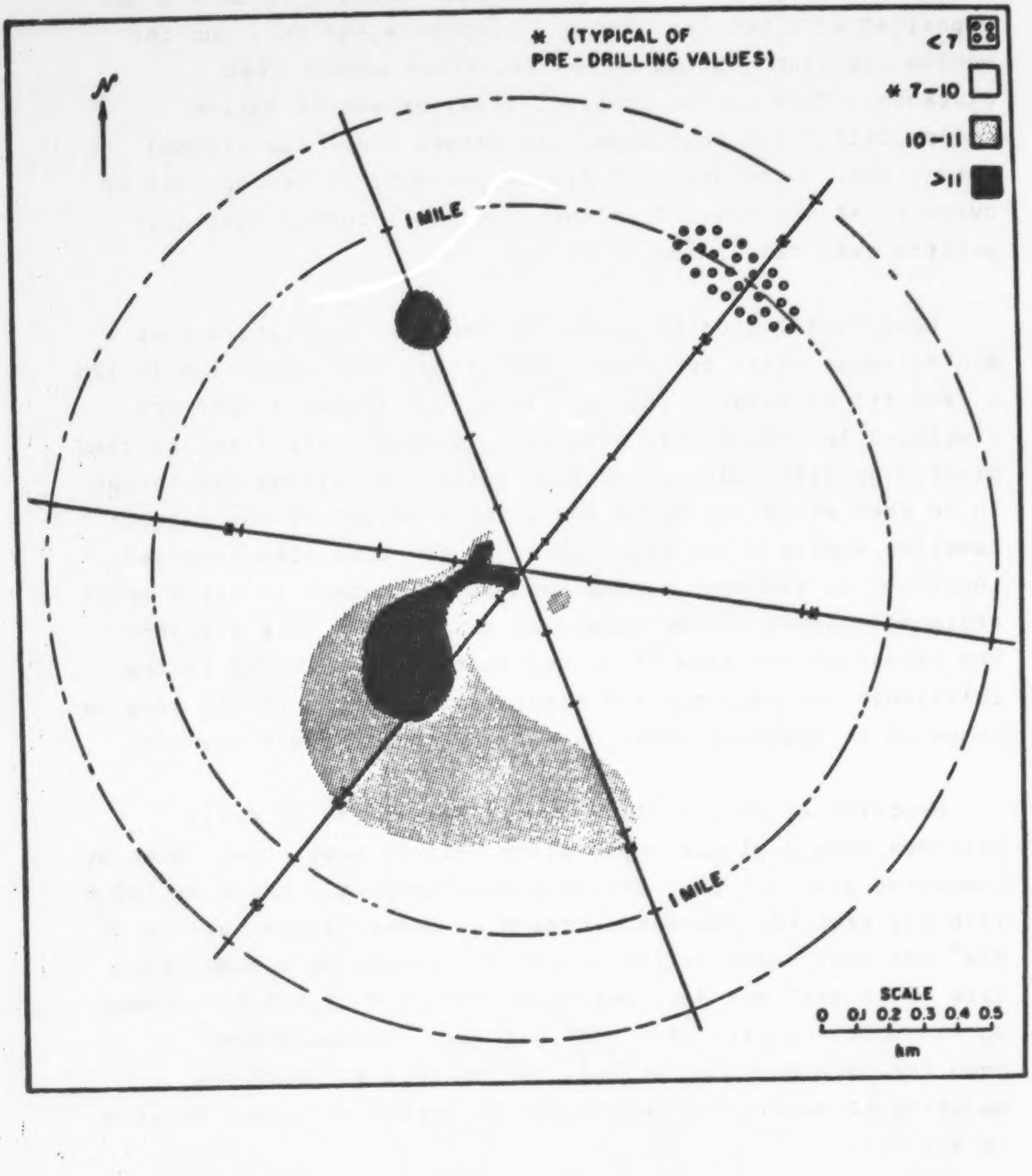
Figure 3-3. Approximate pattern of initial particle deposition (Houghton et al.,1981)

(10 mm-2 mm) deposited within 125 to 175 m (410 to 574 ft) of the discharge point, the intermediate fraction (2 mm-250 µm) deposited at 1,000 to 1,400 m (3,280 to 4,592 ft), and the medium fraction (250 µm-74 µm) deposited beyond that distance. This is the greatest areal extent of bottom sedimentation for continuous discharges under the assumed conditions. Discontinuous discharges will be transported by currents at the time of release, and will form a starburst pattern over time (Zingula, 1975).

EG&G (1982) studied suspended sediment deposition near a Mid-Atlantic outer continental shelf drilling operation in 120 m (400 ft) of water. Post-drilling clay accumulations are displayed in Figure 3-4. The study showed grain size and clay mineralogy distributions were affected by drilling discharges in an area extending up to 800 m for a period of one year. Sampling within a two-mile radius of the well site revealed increases in sediment barium levels and changes in trace metal sediment concentrations extending to at least this distance. The extent of the area of accumulation is attributed to the relatively low currents and greater water depth of the area as compared to those of other outer continental shelf studies.

Houghton et al., (1981) studied deposition of drill cuttings from a single exploratory well in Lower Cook Inlet by comparing pre- and post-drilling core samples. Cores at 100 m (330 ft) from the discharge showed an accumulation rate of 30 g/m^2 per day, cores at 200 m (660 ft) showed an accumulation rate of 10 g/m^2 per day, and cores at 400 m (1,307 ft) showed an accumulation rate of 1 g/m^2 per day. Accumulations occurred to a depth of at least 12 cm (4.7 in) with the majority of cuttings accumulating to depths of 1 to 7 cm (0.4 to 2.7 in).

Figure 3-4 Spatial distribution of clay content in sediments (post-drilling) (Ayers et al., 1982)



Studies have shown the extent of drilling fluid accumulation on the bottom to be inversely related to the energy dynamics of the receiving water. Vertical mixing also appears to be directly related to energy dynamics. Analysis of sediments at Tanner Bank (Ray and Meek, 1980; Meek and Ray, 1980) ten days after the last discharge showed no visible evidence of cuttings or mud accumulation even though over 800,000 kg (882 short tons) of solids had been discharged over an 85 day period. Size analysis also indicated little change in the grain size distribution.

Low energy environments, however, are not subject to currents removing deposited material from the bottom or mixing it into sediments. In the low-energy Mid-Atlantic environment, for example, Menzie (1982) reported that cuttings piles were visibly distinct one year after drilling had ceased. Zingula (1975) also reported visible cuttings pile characteristics in the Gulf of Mexico shortly after drilling had terminated.

One study in the Gulf of Mexico (Ayers et al., 1980b) has examined the short-term sedimentation of drilling fluids and cuttings in 23 m of water. Sediment traps were deployed only to a distance of 200 m. No distance-dependent quantitative estimates were possible from the data. Ten- to 100-fold more material was collected in traps after the 1,000 bbl/hr discharge than after the 275 bbl/hr discharge. The relative barium, chromium, and aluminum contents of collected matter was more similar to that found in the initially discharged fluid for the 1000 bbl/hr discharge than for the 275 bbl/hr discharge. This suggests a reduced influence of differential dispersion of these metals during the higher rate discharge.

Vertical incorporation of plume components into sediments is caused by physical resuspension processes and by biological reworking of sediments. The relative contribution of these processes to mixing has not been quantified. Vertical entrainment occurs, but is not well-described. Petrazzuolo (1981; 1983a) cites a Gulf of Mexico operation where barium concentration was substantially enriched to a 4 cm (1.6 in) depth at both 100 m (330 ft) and 500 m (1,600 ft) distances. The upper 2 cm (0.8 in) of sediment was highly enriched with barium. This study was conducted along one transect (not aligned with major current flows) after four wells had been drilled at the platform.

3.3.1.5 Alterations in Sediment Barium Levels

The long-term fate of discharge drilling fluids has been followed in several studies using sediment barium levels as a tracer. Four studies have been performed in the Gulf of Mexico from which data have been analyzed to estimate the dispersion of sediment barium.

Sediment levels of barium were determined for a shunted discharge in Block 384 of the High Island area, approximately 5,300 m NNE of the West Flower Garden Bank (Union Oil Company, 1977). The rig was located in 104-108 m of water and shunted to a depth of 10 m from the bottom. The post-drilling survey occurred 11-17 days after drilling operations ceased (see Table 3-7).

Sediment barium levels have been determined for a Gulf of Mexico drilling operation in Block A-389 of the High Island

TABLE 3-7 GEOMETRIC REGRESSION COEFFICIENTS AND STATISTICS FOR TOTAL SEDIMENT BARIUM CONCENTRATIONS VERSUS DISTANCE FROM RIG SITE

OCS Study Site	a	b	r^2	SE of the Estimate	df	P
West Flower Garden Bank	24,518	-0.480	0.854	0.169	5	0.0023
Mustang Island	37,142	-0.617	0.974	0.239	1	0.0536
East Flower Garden Bank	24,501	-0.449	0.933	0.143	2	0.0153
Baker Bank, Cruise A	140,185	-0.660	0.902	0.210	2	0.237
Baker Bank, Cruise D	32,302	-0.446	0.876	0.162	2	0.0302
Baker Bank, Cruise J	50,848	-0.521	0.972	0.0858	2	0.0055
Baker Bank Cruise M	550,897	-0.828	0.869	0.310	2	0.0330

Adapted from Petrazzuolo (1983a).

References - West Flower Garden Bank: Union Oil Company 1977
Mustang Island: Department of Interior 1976b
East Flower Garden Bank: Mobil Oil Corporation 1978
Baker Bank: Continental Oil Company 1979

area, approximately 400 m from the "no activity" boundary of the East Flower Bank, in 124 m of water (Mobil Oil Corporation 1978). Two wells were drilled. Discharges were shunted to within 10 m of the bottom. Post-drilling sampling occurred 5-18 days after drilling-related discharges ceased (see Table 3-7).

Sediments metal levels were determined for an exploratory well located in about 36 m of water, near Mustang Island, on the Texas OCS (Department of Interior 1976b). Post-drilling sampling was reported to have occurred approximately three months after drilling operations ceased. Among the metals that were tested (barium, cadmium, chromium, copper, iron, lead, nickel, and vanadium), only barium showed any obvious difference between pre-drilling and post-drilling levels. Four distances were sampled (0 m, 100 m, 500 m, and 1,000 m from the rig) and sediment barium levels at the rig were lower than at 100 m, due to advection of the discharged material.

Sediment levels of barium were determined for a western Gulf of Mexico drilling operation in 75 m of water on the Texas OCS, near Baker Bank in the Mustang Island area (Continental Oil Company, 1979). Sampling occurred during and after the drilling of four wells. Sampling sites were oriented generally to the NW on three closely-aligned radial transects. Replicate values were obtained for four quarterly cruises at distances of 504 m, 1,004 m, 1,506 m, and 3,300 m.

Barium levels in the sediment within about 1,000 m of the rig generally increased with time. However, interpretations of these data are confounded by the presence of other wells that were drilled nearby. The most significant of these included two exploratory wells located 100-150 m west of the study platform.

The data from these four studies have been analyzed using average sediment barium levels (with respect to direction) as a function of radial distance (r) from the discharge source. Regression analyses were performed on log-log transforms of data sets for each study. The results and statistics for the geometric regression analysis for total sediment Barium are presented in Table 3-7. The form of the power law relationship is:

$$Ba_{EXCESS} + Ba_{BGND} = Ba_{TOTAL} = a\ r^{b}$$

The resulting regression analyses for total sediment barium are characterized by good to excellent statistics. All regression coefficients are significantly different from zero, with P-values ranging from 0.0037 to 0.0536, and most of the regressions have a good r^2 statistic (all $r^2 > 0.854$).

Since data were available for sediment barium levels with respect to both distance from the source and number of wells, a multivariate geometric regression was performed. Sediment barium levels were generated from the equations given in Table 3-7 for distances of 100 m, 500 m, and 500 m increments thereafter until either a distance of 5,000 m or a level of 0 ppm excess barium was reached. These data were obtained for an average of the two one-well operations, the two-well operation, and the six-well operation described previously.

The multivariate regression equation of sediment Ba as a function of number of wells (N) and distance from the discharge (r) was:

$$Ba_{TOTAL} = 7.423x10^{5} (N^{1.373})(r^{-1.283}) + Ba_{BGND}$$

The value of r^2 was 0.781 with 116 degrees of freedom. A comparison of the multivariate equation estimates and the bivariate source equation estimates is shown in Table 3-8.

The multivariate analysis for number of wells and distance was used to estimate sediment barium levels at sampling stations 102 m to 29,941 m from Platform "A" after nine wells were drilled (Continental Oil Company 1982). These data include discharge data from three additional wells taken after the Platform "A" data were obtained. Platform "A" data formed part of the multivariate analysis. Comparisons of the estimates from the multivariate analysis and the actual sampling data are presented in Table 3-9.

Only one multivariate estimate fell beyond the sampling value ±1 standard deviation, and this exception was an over-estimate of 18 percent (1,194 ppm versus an observed level of 1,013 ±90 ppm). This analysis suggests that sediment barium data collected early in the development phase of an operation may provide accurate estimates of sediment barium levels later in the operation. However, some qualifications apply.

TABLE 3-8 COMPARISON OF ACTUAL AND PREDICTED LEVELS OF EXCESS SEDIMENT BARIUM

Number of Wells	1		2		6	
Distance (m)	Multivariate Estimate	Bivariate Estimate	Multivariate Estimate	Bivariate Estimate	Multivariate Estimate	Bivariate Estimate
100	2,000 (+9%)	1,832 (1596-2122)**	5,179 (+99%)	2,602 (2582-2622)	23,408 (+47%)	1,591 (11,700-20,100)
500	337 (+11%)	303 (87-406)	655 (-27%)	902 (816-987)	2,960 (+7%)	2,777 (2,743-28,100)
1000	119 (+34%)	89 (24-207)	269 (-50%)	540 (494-485)	1,215 (-4%)	1,272 (733-824)
1500	104 (+181%)	37 (12-138)	160 (-58%)	385 (368-402)	722 (-7%)	779 (733-824)
2000	62 (+130%)	27 (7-103)	110 (-63%)	295 (290-299)	499 (-6%)	533 (516-550)
2500	43 (+95%)	22 (5-82)	83 (-65%)	234 (213-254)	374 (-3%)	386 (378-393)
3000	32 (+78%)	18 (3-68)	66 (-65%)	190 (156-223)	296 (+3%)	287 (259-314)
3500	25 (+67%)	15 (2-59)	54 (+65%)	155 (111-199)	243 (+13%)	216 (172-260)
4000	21 (+62%)	13 (2-51)	45 (-65%)	128 (74-181)	205 (+26%)	163 (104-221)
4500	17 (+42%)	12 (2-45)	39 (-63%)	105 (44-166)	176 (+45%)	121 (51-191)
5000	15 (+36%)	11 (1-41)	34 (-60%)	86 (18-154)	154 (+75%)	88 (8-168)

Adapted from Petrazzuolo (1983a).

TABLE 3-9 COMPARISON OF ACTUAL AND PREDICTED SEDIMENT BARIUM CONCENTRATIONS AROUND A GULF OF MEXICO PRODUCTION PLATFORM AS A FUNCTION OF DISTANCE FROM THE RIG AND NUMBER OF WELLS*

Number of Wells	Distance	Sediment Barium, ppm (mg/kg)		
		Actual	Calculated**	1% Difference
9	2385	1013±90***	1195	(+18%)
9	102	46,692±3657*** (39,584-46,590)	40,300	(-8%)
9	12,073	637±88*** (552-728)	586	(8%)
9	29,941	517±30*** (483-541)	527	(+2%)

* Adapted from Continental Oil Company (1982), as in Petrazzuolo (1983a).

** Background level set at 500 ppm Ba; calculated value determined from:

$$Ba_{TOT} = 7.423 \times 10^5 \; (N^{1.373})(r^{-1.285}) + Ba_{BGND}$$

*** Mean ± standard deviation (n = 3)

This analysis represents the first preliminary effort at predicting sediment barium levels from multiple well operations. Although there are limitations in the available data base, these limitations are not as important as the establishment of a framework for the analysis of multiple well effects. However, at least three identified limitations exist: the lack of accurate barium discharge data, the effect of differences in time scales for drilling multiple wells, and geographic differences.

The first problem with the data base used in this approach is that using "number" of wells is not as good a variable as an accurate estimate of the amount of barium (as barite) discharged. Lacking such data, however, the number of wells must be considered a first-order approximation.

A second factor that needs further assessment is the effect of time scale on the sediment barium dispersion equations. The data base used in this analysis relies on sediment sampling conducted shortly (two weeks to three months) after drilling ceased, or during drilling for a multiple well operation. These data reflect a discreet position of a dynamic equilibrium between the accretion of drilling fluid solids in the sediment and dispersive forces action on this sediment. The difference in time scales, and therefore dispersive processes, involved in drilling 6-10 wells is far different than drilling 60-100 wells.

The third consideration is that of the site-specific nature of dispersion processes. A better understanding of more fundamental processes is required before quantitative comparison between different areas can be made confidently.

One study has attempted to perform a quantitative correlation of the amount of material discharged versus its spatial distribution in the sediment (Mobil Oil Corporation 1978). In this study, an estimate of the quantity of barium deposited in the sediment was performed by comparing the area of a series of concentric rings about the platform to that of a single core, and calculating average barium levels in this "ring" based on (a) the observed barium levels in samples obtained at discreet distances from the platform, and (b) the dry weight of the sediment from a core. This analysis indicated that about 40 percent of the discharge barium was found outside a radius of 1,250 m from the platform.

These same data can be analyzed using a different approach. Another method to estimate the total amount of sediment barium within a given radius of the drillsite is to obtain a function that describes the decrease in barium levels with distance and integrate it with respect to both distance and direction. From the studies cited above, it appears that a fairly consistent function that describes the distance-dependent relationship is: $[Ba] = a\ r^b$. The required integration, with respect to both distance and direction, is given by:

$$\int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} (a\ r^b\ dr)(r\ d\theta)$$

Therefore, the cumulative concentration-area product of the double integral is given by:

$$\Big|_{0}^{r} \quad 2\pi a\, r^{2+b} \Big/ (2+b)$$

If the distance is set at 1,250 m and the site-specific value of b is used (i.e., b = 0.449), the estimates for this drilling operation are 56,750 kg (78 percent) within 1,000 m of the platform and 80,300 kg (111 percent) within 1,250 m of the platform.

3.3.1.6 Trace Metal and Physical Benthic Alterations

An environmental study (Department of Interior, 1976a) was conducted in approximately 33 m of water on the south Texas outer continental shelf (Block 755, Mustang Island Lease Area). The trace metal content of suspended sediments was not thought to have been affected from drilling activities, although seasonal variations and the effect of ship traffic from the nearby Port Aransas shipping lanes confound the interpretation of these results.

Lead has a 2.7-fold increase in the sediment at the drillsite and a 1.9-fold increase at 1,000 m stations. At the drillsite, zinc was elevated 2.5- to 3.5-fold and cadmium was elevated 3- to 9-fold. These metals showed low levels, similar to those taken before drilling, in the sediment 300 m from the drill site.

Comparisons of textural variability between the composite pre-drilling and post-drilling sample suites showed significant differences (95 percent confidence level) for skewness, silt percentage, clay percentage, silt/clay ratio, and mean diameter. The post-drilling site was significantly coarser-grained, had a higher silt/clay ratio, and was less coarsely skewed than the pre-drilling suite. No valid conclusions were thought possible regarding the causes of the textural differences.

A rig monitoring survey was conducted at an exploratory site located near the north lease line of Mustang Island (Texas), Block 792, in 36 m of water (Department of Interior, 1976b). Significant changes in the levels of sand, clay, silt, and $CaCO_3$ occurred between before versus during drilling phases. Sand, clay, and $CaCO_3$ levels increased significantly, while silt levels showed a significant decrease. Comparison of the during- and after-drilling levels showed that the clay and $CaCO_3$ levels decreased significantly and silt levels increased significantly. These authors examined the metal/iron ratio for chromium, copper, lead, nickel, and vanadium. The data indicated that no spatial trends existed in the metal concentrations.

An environmental study in the central Gulf of Mexico has examined chronic, low-level, heavy metal contamination from active petroleum production platforms on the OCS (Tillery and Thomas, 1980). Results from sediment chemistry data showed concentration gradients that decreased with distance from the platforms for barium, cadmium, chromium, copper, nickel, lead, vanadium, and zinc at one or more platforms. These gradients were not explained by the variability in sediment characteristics.

A study has investigated the environmental distribution of metals from drilling fluids discharged into the Beaufort Sea, near the Mackenzie River Delta (Crippen et al., 1980). Mercury contamination of sediments was obvious within 100 m of the point of discharge, and mercury levels were somewhat elevated above mean background levels (0.07 µg/g) at several other stations. The highest mean value recorded was 6.4 µg/g located less than 45 m from the shoreline of the island, just north of the discharge.

The concentrations of arsenic, cadmium, chromium, lead, and zinc in surface sediments exceeded background levels at one or more stations in the vicinity of the discharge. Subsurface concentrations of most metals, excluding chromium, were substantially higher than surface sediment sample 45 m SW of this discharge location. This sample was thought to be a pocket of drilling fluid from operations prior to the use of chrome lignosulfonate.

A study was conducted to monitor the environment fate associated with above-ice disposal of drilling fluids and cuttings in the Beaufort Sea (Sohio Alaska Petroleum Company 1982). Three wells were sampled, Sagavanirktok Delta Wells #7 and #8 (Sag 7 and Sag 8), and Challenge Island Well #1 (Challenge 1). Three sites (A, B, and C) were sampled at Challenge 1.

F-test analyses indicated that there were no significant differences ($P < 0.05$) among any pre- versus post-discharge tests at disposal sites. For post-discharge tests of disposal sites versus reference sites, a few significant differences were found. Median grain size decreased at Sag 8 and Challenge 1 (Site C) for the >0.25 mm (percentage coarser) fraction and at Sag 8 for the >0.150 mm fraction. Increased median grain size occurred for the >0.250 mm fraction at Challenge 1 (Sites A and B) and for the >0.150 mm fraction (Site B).

Trace metal analyses were conducted on samples of drilling fluids that were disposed. Comparison of pre- and post-discharge bottom sediment samples from Sag 7 indicated significant decreases in levels of barium, cadmium, and mercury that were judged unrelated to drilling fluids. Analyses of samples from Sag 8 indicated only that Ba levels decreased significantly.

Analyses of Challenge 1 samples indicated significant increases in levels of cadmium, chromium, lead, and zinc at Sites A and B, and in copper, lead, and zinc at Site C. Increases of chromium and zinc were considered related to drilling fluids disposal. Cadmium data were not considered to be explained by effluent discharges because cadmium levels in the effluents and pre-discharge sediments were similar. Elevations in lead were not judged to be drilling fluid-related because of spatial patterns, other sediment characteristics, and because Site C did not melt in place.

However, elevations of cadmium and lead levels could be effluent-related. Although cadmium levels in early drilling fluid samples (0.2 mg/kg) were similar to pre-discharge sediment levels (0.19-0.35 mg/kg), an enrichment of cadmium in drilling fluid effluents occurred at all disposal sites over time, to 0.8-1.1 mg/kg. Also, for cadmium, chromium, lead, and zinc sediment levels were inversely related to distance from disposal sites (A and B) for 0-60 m, 60-85 m, and 250 m data sets.

Furthermore, for cadmium, lead, and zinc at Sag 7 and chromium, copper, lead, and zinc at Sag 8, a consistent spatial pattern of enrichment at the nearfield stations (approximately 85-200 m) occurred relative to pre-discharge levels and either within-site or far-field (315-585 m) stations. These enrichments were not statistically significant. However, trace metal levels had 95 percent confidence levels that averaged about 65 percent of the mean. This large variability substantially reduces the ability to statistically resolve differences among data sets.

Nonetheless, near-field enrichments were consistent. For both lead and zinc, enrichment was 1.3-fold at Sag 7 and 1.2-fold at Sag 8, versus 2.3- to 2.6-fold for lead and 1.4-fold for zinc at Challenge 1. Chromium levels at Sag 7 increased 2-fold versus 1.4-fold at Challenge 1.

A study has assessed the impacts of above-ice drilling effluent disposal techniques in the Beaufort Sea (Sohio Alaska Petroleum Company, 1981), between the Midway Islands and Prudhoe Bay. A simulated, above-ice disposal test was conducted.

Grain size analyses of settling pan sediment indicated that a rapid decrease in deposition rates occurred for most particle sizes. At the center of the discharge hole, deposition was

729 mg/cm^2 for all grain size fractions. At 1.5 m and 3.0 m, average deposition was 313 mg/cm^2 and 168 mg/cm^2, respectively. It was estimated that the average deposition of all particle sizes was about 200 mg/cm^2 over the test site. The average deposition rate for particles less than 45 microns, measured 3 m from the discharge point, was in the same general range of deposition rates measured at two below-ice disposal sites (166 mg/cm^2 versus 66-368 mg/cm^2, respectively). Bottom sediment trace metal levels indicated the presence of drilling effluents three days after the discharge, but not three months post-discharge.

Trace metal analyses of drilling fluid samples and sediments were conducted both within and near the disposal sites. At one site there were no notable differences as a result of drilling activities. At the second site, however, three metals showed possible enrichment: cobalt, copper, and iron.

These sediment metal studies, when considered as a group (Table 3-10), suggest the enrichment of certain metals in surficial sediments may occur as a result of drilling activities. While confounding factors occur in most of these studies (i.e., seasonal variability and other natural and anthropogenic sources of these metals) a distance-dependent decrease in metal levels frequently is observed. However, although drilling activities are implicated as a source of metal enrichment, discharged drilling fluids and cuttings probably are not the only drilling-related source.

TABLE 3-10 SUMMARY OF SEDIMENT TRACE METAL ALTERATIONS FROM DRILLING ACTIVITIES[a]

Location	Trace Metal								
	As	Cd	Cr	Cu	Hg	Ni	Pb	V	Zn
Gulf of Mexico, Mustang Island Area suspended sediment	ND	-	+ (8-31x)	± (7-10x)	ND	-	-	± (6-25x)	-
Surficial sediment	ND	+ (3-9x)	-	-	ND	-	-	-	+ (2.5-3.5x)
Gulf of Mexico, Mustang Island Area	ND	±	±	±	ND	±	-	-	ND
Central Gulf of Mexico	ND	+	+	+	ND	+	+	+	
Mid Atlantic	-	-	-	-	BLD	+ (2.5x)	+ (4-4x)	+ (2-9.5x)	+ (4x)
Mackenzie River Delta	+ (1.2-2.5)	+ (2-6x)	+ (4-7x)	ND	+ (1.2-15x)	ND	+ (1.5-2.2x)	ND	+ (11.7x)
Beaufort Sea	ND	+ (2-6x)	+ (1.4-2x)	±	-	ND	+ (1.2-2.6x)	ND	+ (1.2-1.4x)

a. Adapted from Department of Interior (1976a, 1976b, 1977); Tillery and Thomas (1980); Mariani et al., (1980); Crippen et al., (1980) after Petrazzuolo (1983a).

Abbreviations:
- ND (not determined)
- + (increased levels (magnitude change in parentheses) related to drilling)
- - (decreased levels related to drilling)
- ± (isolated increases, not a clearly distance-related pattern)
- BLD (below the level of detection)

The only two metals that appear to be elevated around rigs or platforms, and are clearly associated with drilling fluids, are barium and chromium. A study in the Canadian Arctic found that mercury would be the best trace metal tracer of discharged fluids. Examination of mercury levels in fluids and sediments for domestic operations is notably under-represented in the studies that have been reviewed. The degree of similarity between Canadian and domestic operations has not been evaluated. However, the findings of the Netserk study and lack of information on domestic operations indicate that the relationship between drilling fluid discharges and sediment mercury levels should be further clarified.

Metals that appear to be elevated as a result of drilling activities, and not solely related to drilling fluids, include cadmium, mercury, nickel, lead, vanadium, and zinc. Cadmium, lead, and zinc may be associated with drilling fluids as contaminants that occur from the use of pipe dope or pipe thread compounds. Mercury, nickel, and zinc may originate from sacrificial anodes. Cadmium, lead, and vanadium may also originate from the release of fossil fuel in drilling operations. This release can result from burning, incidental discharges or spills from the rig or supply boat traffic, or use as a lubricant in drilling fluids. Vanadium also may derive from wearing of drill bits. In the Gulf of Mexico platform study, brine (formation water) discharges were identified as an additional potential source of metal contamination.

Although these metals were enriched in the sediment, enrichment factors were generally low to moderate, seldom exceeding a factor of 10. The spatial extent of this enrichment also was limited. Either of two cases occurred: enrichment was generally distributed but undetectable beyond 300-500 m or enrichment was directionally-based by bottom current flows and extended further (to about 1,800 m) but within a smaller angular component.

These considerations suggest that exploratory activities will not result in environmentally significant levels of trace metal contamination. However, other factors, such as the intensity of exploratory activities, normal sediment loading, and proximity either to commercial shell fisheries or to subsistence populations, could alter this conclusion. Sediment trace metal levels resulting from development drilling operations need further clarification, especially relating to the dynamics and extent of sediment contamination.

3.3.2 Produced Water

The Corvallis Environmental Research Laboratory, which is part of the Ocean Discharge Division of EPA's Narragansett Environmental Research Laboratory (ERL), has developed a PLUME model that calculates height-of-rise and near-field initial dilution from a discharge. These calculations are required by regulations issued by the EPA to implement Section 301(h) and 403(c) of the Clean Water Act. Typical applications of this model, the PLUME model, have been for municipal ocean discharges. The PLUME model is described in detail in two reports (Baumgartner et al., 1971; Teeter and Baumgartner, 1979).

The PLUME model was recently modified to predict dilution, trap depth, and depth of maximum penetration of produced water discharges from platforms. This model's predictions seem to compare favorably with laboratory experiments for discharges of drilling fluids and brine. Maximum discharge volumes for platform sizes projected to be located in shallow water are shown in Table 3-11. Average discharge volumes for various platform sizes are shown in Table 3-12. Initial PLUME model computer runs evaluated discharges of 3,000, 10,000, 25,000 and 50,000 bbl per day. Lower and upper specific gravity values of actual brine discharges were used: 1.073 and 1.151 g/ml, which corresponds to 80,500 mg/liter and 203,000 mg/liter total dissolved solids (TDS), respectively.

PLUME model results are shown in Table 3-13. The table presents the maximum depth of penetration of the discharge plume, the center line dilution of the plume at the trap depth, and the typical platform sizes modelled. The trap depth of the plume is where the plume's density matches the density of the receiving waters. However, because of the momentum of the jet, the plume penetrates below the trap depth, to a maximum depth of penetration. Table 3-13 assumes no current and an assumed density profile for ocean environments. Table 3-14 presents typical water depths in state waters for comparison to maximum depths of penetration in Table 3-13.

TABLE 3-11

MAXIMUM DISCHARGE FLOW (bbl/day) AND NUMBER OF PLATFORMS IN WATER LESS THAN VARIABLE DEPTHS

Platform Size	Oil		Oil and Gas	
	Max. Flow	No. Platforms	Max. Flow	No. Platforms
Gulf 4	2051	6	2122	28
Gulf 2x6	5129	12	5184	38
Gulf 12	5103	3	5213	14
Gulf 24	9287	0	9519	0
Gulf 40	16558	0	16847	0
Gulf 58	25880	0	26334	0
		21		80
Pac 16	5999	0	6081	0
Pac 40		0	14000	0
Pac 34		0	35000	2
		0		2
Beaufort[1] 48	66021	6		
Berin Platform 48	80294	0		
Beaufort[2] 48	94316	0		
		6		

---

[1] Gravel Island

[2] Platform

TABLE 3-12
AVERAGE DAILY
PRODUCED WATER VOLUMES (bbl/day)
FOR THE MODEL PLATFORMS

Model Platforms (Wells/platform)		Type of Platform		
		Oil	Oil-Gas	Gas
Gulf	12	3,086	3,259	410
	24	5,672	5,819	217[1]
	40	9,563	10,104	
	58	14,382	15,237	
Pacific	16	3,465	3,694	551
	40	8,081	8,345	
	34[2]	20,606	21,250	
Atlantic	24	11,414	11,823	2,376
Cook Inlet, AK		20,609	20,608	1,614
Beaufort Sea, AK[3]		34,470	34,470	
Bering Sea, AK		44,831	46,391	
Beaufort, AK[4]		46,615	49,242	

[1] Assumed geopressured reservoir

[2] Assumed very productive field for model

[3] Gravel Island

[4] Platform

TABLE 3-13

PREDICTED MAXIMUM PLUME DEPTH AND PLUME CENTERLINE DILUTION[1]

Depths(m) of water Column (m)	Produced water Discharge Rate bbl/day	3,000	Centerline Dilution at trap depth**	10,000	Centerline Dilution at trap depth	25,000	Centerline Dilution at trap depth	50,000	Centerline Dilution at trap depth	Assumed Conditions[3]
10		Bottom		Bottom		Bottom		Bottom		Unstratified
10		7-9	28-56	Bottom	21*	Bottom	17-31	Bottom	14*	Stratified
20		9-12	44-86	12-15	32*	16-Bottom	26-57	Bottom		Stratified
30		11-13	57-111	14-18	42*	18-23	32-65	22-27	28*	Stratified
100		35-37	704-951	23-40	89*	40-44	186-265	43-49	121-182	Top 30 m mixed layer, stratified below 30 m
Model platforms sizes (wells/platform)		Gulf-12	Pacific-16	Gulf-40 Atlantic-24	Pacific-40	Pacific-34[2]	Cook Inlet, AK	Bering Sea, AK	Beaufort, AK	

[1] PLUME Model was used as developed by Environmental Research Laboratory-Corvallis

[2] Assumed very productive field for model

[3] Assumed no current in all cases and 1.073 g/ml and 1.151 g/ml density of discharge

*Dilution at trap depth for discharge density of 1.073 g/ml only

**Average dilution equals 1.77 multiplied by centerline dilution.

TABLE 3-14 AVERAGE DEPTH OF STATE WATERS

Texas* (3 leagues)	Louisiana	Southern California	Northern California	Cook Inlet,AK	Bering Sea,AK	Beaufort AK
12 m	5 m	150 m	150 m	24 m	Norton Sound-4 m N. Aleutian Basin-10 m	3 m

*All state waters in this table extend 3 miles offshore except Texas which has three league designation (approximately nine miles).

For the platform sizes projected to be located within territorial seas (Table 3-14), comparisons of their depths of penetration from Table 3-13 to actual water depths reveal areas where potential direct benthic impacts may occur due to bottom impact of the plume and pollutant accumulation in the sediment. The results shown in Table 3-13 are summarized below:

(1) Direct benthic impacts are possible in the territorial seas of Texas and Louisiana. The average depth in the territorial seas for these states is approximately five meters. The average depth of state waters could be higher than this because of Texas' state water boundary of three leagues (nine miles from shore). The discharge from a model 12-well platform is projected to reach the bottom in water depths of less than nine meters. For the majority of both oil and oil-gas model platform sizes, plumes will impact the bottom in state waters and the territorial seas because water depth averages approximately five and nine meters, respectively. Gas platforms were not modelled because of their low discharge volumes.

(2) Larger platforms (40 to 58 wells) could cause impacts in Federal waters because the discharge plume is projected to descend to almost 20 meters. The water depth in certain Federal waters off the Texas and Louisiana coasts is considerably less than 20 meters.

(3) Plume model runs for other platform sizes, projected to be located in the territorial seas in the Pacific

> (40 wells/platform) and in the Beaufort Sea, Alaska, show that the plume could impact the bottom in water depths of approximately 20 meters or less. The average water depth in California's territorial seas is 150 meters which should provide adequate protection to the benthos. However, state waters in the Beaufort Sea are an average of three meters deep, and impacts may occur.

In an effort to evaluate the impact of currents on dilution and depth of penetration of the plume, another model UMERGE (Soldate et al., unpublished) was used, which evaluated the PLUME model, assuming a water column depth of 20 meters and currents of 0, 2, 5, 10, 20, and 50 cm/sec. The results of this analysis are shown in Table 3-15. These results show the cross-sectional average dilution of the plume at any given depth instead of center line dilution of the plume. The average dilution is higher than the center line dilution because more area is involved in the mixing calculation. From Table 3-15, the maximum depth of penetration decreases, and the average dilution increases as the current increases.

During the Buccaneer Field Study in the Gulf of Mexico, a discharge plume was dye marked (discharge volumes of approximately 600 bbl/day) and under calm conditions was reported to penetrate to water depths of 10 meters from the surface. Table 3-15 only shows a 3,000 bbl/day discharge, which penetrates 8.9 to 11.3 meters, depending on the density of the wastewater discharge and the ambient density stratification. In order to better approximate a lower volume discharge, such as in the Buccaneer Field, actual density

TABLE 3-15

PLUME OUTPUT WITH CURRENTS

Currents	Produced Water Volume BPD	6" Pipe Diameter 3000			5000			12" Pipe Diameter 10000			16000		
	1	8.5[A]		135[B]	9.7		119	11.5		100	12.8		89
0 cm/sec			11.3[C]			12.8			15.1			17	
	2	6.7		73	7.5		64						
			8.9			10.0							
	1	8.5		136	9.6		119	11.4		100	12.8		89
2 cm/sec			11.2			12.7			15.1			17	
	2	6.7		74	7.5		65						
			8.8			9.9							
	1	7.8		167	9.1		139	11.1		110	12.6		95
5 cm/sec			9.7			11.4			14.1			16.1	
	2	5.8		100	6.8		81						
			7.1			8.5							
	1	5.7		291	7.0		225						
10 cm/sec			6.8			8.4							
	2	3.9		185	4.9		146						
			4.7			5.8							
	1	3.4		448	4.2		374	5.6		290	6.9		241
20 cm/sec			4.2			5.1			6.8			8.3	
	2	2.3		259	2.9		218						
			2.9			3.6							
	1	2.1		614	2.6		518	3.9		411	3.8		352
50 cm/sec			2.7			3.2			4.1			4.7	
	2	1.6		351	1.9		297						
			2.0			2.4							

Assumes stratified water column of 20 meter depth.

A trap depth (m)
B dilution at trap depth (ave.)
C max penetration (m)

1 discharge (gm/ml) 1.151
2 discharge (gm/ml) 1.073

NOTE - Max depth of penetration decreases as current increases.
Dilution increases as current increases.

profiles for 1979 from the Buccaneer Field (Table 3-16), and lower discharge volumes were used. The results of this analysis are shown in Table 3-17.

The density profile of the water column is an important factor in the estimates of plume penetration and dilution. Seasonal stratification due to temperature or salinity gradients can significantly influence the depth of penetration. This was discussed in Section 3.3.1.2. The results in Table 3-17 show that the plume penetrates to the bottom (19 meters in this case) given winter and fall density profiles for 1979. This was further than originally estimated in Table 3-13 for a slightly higher value of 3000 bbl/day. Under certain conditions i.e., no currents or lower currents, higher dissolved solids content, and certain density profiles, the plume is projected to penetrate even further than was projected earlier.

3.4 CHEMICAL TRANSPORT PROCESSES

3.4.1 Drilling Fluids

3.4.1.1 Inorganics

Most research on chemical transport processes affecting offshore oil and gas discharges focuses on trace metal and hydrocarbon components. The trace metals of interest in drilling fluids include barium, chromium, lead, and zinc. The source of barium in drilling fluids is barite; barite may be contaminated with several metals of interest, including arsenic, cadmium, lead, mercury, zinc, and other substances (Table 3-18). These trace metals are discussed below as they pertain to chemical transport processes.

TABLE 3-16 BUCCANEER TEMPERATURE AND SALINITY PROFILES

	Summer 1979			Fall 1979			Winter 1979			Spring 1979		
	Depth (m)	Temp C°	Salinity (ppt)	Depth (m)	Temp C°	Salinity (ppt)	Depth (m)	Temp C°	Salinity (ppt)	Depth (m)	Temp C°	Salinity (ppt)
A	1	29.3	32.5	1-3	24.1	34.8				1	23.5	30.0
B							2-8	14.0	34.6			
C										3	23.3	30.2
D				4	24.3	35.2						
E										5	23.2	30.8
F	6	29.4	32.8	6	24.4	35.4				6	23.2	31.0
G	9	29.4	33.0									
H	11	29.3	33.2				11	12.5	34.4			
I							12	12.5	34.8	12	22.8	32.6
J				13	24.7	35.7						
K							14	12.0	34.6			
L	16	29.3	34.2							16	22.4	33.2
M	19	29.0	34.6	19	24.7	35.7	19	12.0	34.6	19	22.0	34.0

TABLE 3-17

PLUME MODEL COMPUTER RUNS USING ACTUAL WATER COLUMN DENSITY PROFILES FROM THE GULF OF MEXICO, BUCCANEER FIELD STUDY

Maximum Depth of Penetration (meters) and Trap Depth (meters)

Season	Discharge Volumes	1,000 bbl/day	5,000 bbl/day
Summer 1979		13.9 (10)	18.0 (13)
Fall 1979		19.0 (bottom)	19.0 (bottom)
Winter 1979		18.2 (11)	19.0 (bottom)
Spring 1979		9.0 (6.8)	14.0 (10)

Assumes density of discharge 1.151 g/ml.
Assumes no current and a six inch diameter pipe.

TABLE 3-18 CONCENTRATION OF TRACE METALS IN BARITE

	Samples used in solubility studies		Values from literature review	
Metal	High trace metal sample	Low trace metal sample	Vein deposits	Bedded deposits
Arsenic	67	1.8	7[a]	500[b]
Cadmium	12	0.65	0.2-19	50[b]
Cobalt	5.4	2.2	ND	<5-60
Copper	91	7.6	2-97	3-20
Lead	1,370	0.95	4-1,220	<10
Mercury	8.1	0.13	0.06-14	0.06-0.19
Nickel	33	5.7	19[c]	<5-5
Zinc	2,750	9.8	10-4,100	200[b]

(Adapted from Kramer, 1980)

ND = Not detected.

[a] One analysis.

[b] Semiquantitative emission spectrographic analysis.

[c] Mean of 83 analyses.

Kramer et al., (1980) found that seawater solubilities for trace metals associated with powdered barite generally result in concentrations below background levels. Exceptions were lead and zinc sulfides, which may be released at levels sufficient to raise concentrations in excess of ambient seawater levels. MacDonald (1981) found that less than five percent of metals in the sulfide phase is released to seawater.

Barite solubility in the ocean is controlled by the sulfate solubility equilibrium, which becomes saturated at concentrations of 30 to 40 µg/l (Houghton et al., 1981). Background sulfate concentrations in seawater are generally high enough for discharged $BaSO_4$ to remain a precipitate and settle to sea bottom.

Chromium discharged in drilling fluids is primarily adsorbed on clay and silt particles, although some exists as a free complex with soluble organic compounds. Chromium is added to the mud system predominantly in the trivalent state as chrome or ferrochrome lignosulfonate, or chrome-treated lignite. It may be added in the hexavalent state as a lignosulfonate extender, in the form of soluble chromates. The hexavalent form is believed to be largely converted to the less toxic trivalent form by reducing conditions downhole. The most probable environmental fate of trivalent chromium is precipitation as a hydroxide or oxide at pH > 5. Transformation to hexavalent chromium in natural waters is likely only when there is a large excess of manganese dioxide. Simple oxidation by oxygen to the hexavalent state is very slow, and not significant in comparison with other processes (Schroeder and Lee, 1975).

Dissolved metals tend to form insoluble complexes through adsorption on fine-grained suspended solids and organic matter, both of which are efficient scavengers of trace metals and other contaminants. Laboratory studies indicate that a majority of trace metals are associated with settleable solids < 8 μm in size (Houghton et al., 1981).

Trace metals, adsorbed to clay particles and settling to the bottom, are subjected to different chemical conditions and processes than when suspended in the water column. These sorbed metals can be in a form available to bacteria and other organisms if located at a clay lattice edge or at an adsorption site (Houghton et al., 1981). If the sediments become anoxic, conversion of metals to insoluble sulfides is the most probable reaction, and the metals are then removed from the water column. Environments that experience episodic sediment resuspension favor metal release if reducing conditions existed previously in buried sediments; such current conditions also allow further exposure of organic matter complexes for further reduction and eventual release.

3.4.1.2 Organics

The only data generated to date on the partitioning of organics in drilling muds were generated in a laboratory study on admixtures of generic mud No. 8 with 5 percent high-sulfur diesel oil (Breteler et al., 1984). Admixture of the oil into the drilling mud resulted in recovery from the mixture of 42 percent (4-hr mixture) or 45 percent (10 min mixture) of hydrocarbons admixed. Longer mixing time (4 hours) resulted in nearly complete evaporation of the lower alkylated benzenes and other alkanes below C_{10}.

After 10 minutes of mixing and a one hour settling time for a one percent mud/seawater mixture, 30 percent of the hydrocarbons were in the suspended particulate phase, with five percent suspended and the remaining 25 percent in the aqueous phase. The aqueous phase was relatively enriched in C_{10} alkanes. Neither C_1-C_6 benzenes nor C_{10} alkanes were present in the suspended phase. The suspended phase was enriched in alkylated naphthalenes and phenanthrenes, except for C_3 phenanthrene. Suspended particulate phase (aqueous suspended) was enriched in C_0-C_4 (not $C_5$and C_6) benzenes, C_0-C_3 (not C_4) naphthalene and C_0-C_2 (not C_3) phenanthrene.

Proportionately, naphthalenes, accounted for 84 percent of aromatics and 51 percent of total organics in the suspended phase as compared to 58 percent of aromatics and 17 percent of total organics (recovered) in the whole mud (10 minute mixing; 1 hour settling). Mixing for 4 hours rather than 10 minutes decreased hydrocarbons in settleable muds from 70 percent to 20 percent of total hydrocarbons recovered. Aqueous phase hydrocarbon content increased from 25 to 62 percent of the total. Particulate phase hydrocarbons increased from 5 to 18 percent of the total. After 4 hours, enrichment of the aqueous phase was limited to C_2-C_6 benzenes and C_0 naphthalene, whereas the particulate phase was enriched in C_1-C_4 naphthalenes and C_0-C_3 phenanthrenes, while alkylated benzenes were again absent from the particulate phase.

When a 0.1 percent mud to seawater ratio was used, 10 minutes of mixing followed by one hour settling resulted in recovery of 98 percent of alkylated hydrocarbons in the suspended particulated phase, of which only 4 percent were in the suspended phase. The suspended phase was enriched in C_2-C_4 naphthalene and C_0-C_3 phenanthrenes. After 4 hours of mixing and one hour settling, 99.7 percent of hydrocarbons were contained in the suspended particulate phase with 35 percent in the suspended phase. The suspended phase was enriched in C_{10} n-alkanes but not in any other hydrocarbon. The aqueous phase however, was enriched in C_0-C_3 naphthalenes and C_0 phenanthrene. Overall recovery of aromatic hydrocarbons in this experiment, however, was very low, thus hindering the interpretation of these data.

3.4.2 Produced Water

Chemical processes important to the fate of produced water constituents generally are those that affect metal and petroleum hydrocarbon behavior in marine systems. Factors affecting metals have been described above under drilling fluids. Here, the processes affecting petroleum hydrocarbons are briefly described.

Perhaps the most important factor affecting the fate of hydrocarbons in produced water is volatilization. Produced water contains a high fraction of volatile compounds (e.g., benzene), which will be lost from the system over time depending upon their volatility. For higher molecular weight compounds the major processes involve biodegradation of compounds over time. Polynuclear aromatic hydrocarbons tend to be more resistant to such degradation and, thus, can persist in the environment (primarily sediment) for extended periods.

3.5 BIOLOGICAL TRANSPORT PROCESSES

Biological transport processes occur when an organism performs an activity with one or more of the following results:

- an element or compound is removed from the water column;
- a soluble element or compound is relocated within the water column;
- an insoluble form of an element or compound is made available to the water column;
- an insoluble form of an element or compound is relocated.

Biological transport processes include bioaccumulation in soft and hard tissues, biomagnification, ingestion and excretion in fecal pellets, and reworking of sediment to move material to deeper layers (bioturbation).

3.5.1 Bioaccumulation

Bioaccumulation is the ability to concentrate substances, including nutrients, naturally-occurring substances, and xenobiotics, to levels above ambient concentrations. Laboratory studies have shown that bioaccumulation of trace metals can be reversed, at least in part. When an organism is transferred from a contaminated environment to a clean one, there generally occurs a decrease in pollutant concentration in the organism.

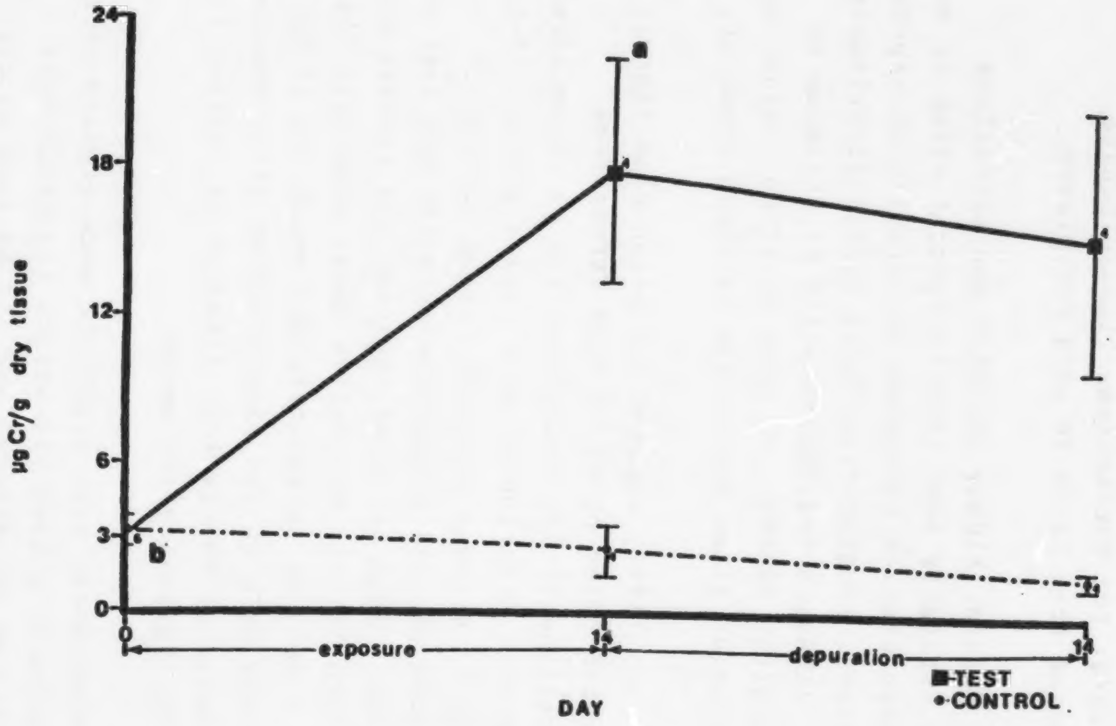
3.5.1.1 Drilling Fluids

The majority of research on metal accumulation from drilling fluids has focused on barite (barium) and ferrochrome lignosulfonate (chromium). Liss et al., (1980) examined chromium accumulation in sea scallops (Placopecten magellanicus) exposed to one part per thousand of used and unused drilling muds and 0.03-1.0 parts per thousand ferrochrome lignosulfonate. They found that chromium did not concentrate in the adductor muscle, but did concentrate in the kidney. Scallops exposed to used and unused drilling fluids accumulated chromium in the kidney at concentrations ranging from two to four µg/g; for ferrochrome lignosulfonate, concentrations ranged from 16 to 70 µg/g dry tissue.

Once exposure ceased, kidney chromium concentrations decreased slowly; typically less than 10 percent after 24 hours (Figure 3-5). These studies represent the results of exposures of small sample sizes, ranging from three to six individuals. McCulloch et al., (1980) noted accumulation of chromium in clams and oysters after exposure to used drilling fluids, but little net accumulation after depuration in clean seawater.

McCulloch et al., (1980) exposed the marsh clam (Rangia cuneata) to a layered solid phase of used ferrochrome lignosulfonate drilling fluid, containing 485 mg chromium/kg. The mean chromium concentration in soft tissue after a 24-hour exposure was about five times the level found in control animals. Two-thirds of this excess accumulation was lost after 24 hours depuration. When the same organism was exposed to the mud aqueous fraction of this mud for 16 days, mean soft tissue levels increased from 7 mg chromium/kg dry weight to 18 mg chromium/kg. Nearly half of the excess accumulation was lost in the first 24 hours of depuration, although no further loss occurred during the following two weeks.

In a third experiment, test organisms were exposed to the mud aqueous fraction of a used mid-weight lignosulfonate drilling fluid (417 mg chromium/kg and 915 mg lead/kg dry weight). Mean soft body concentrations of chromium and lead increased by a factor of 1.5 after three days. Approximately



a standard deviation

b number of organisms

Figure 3-5. Chromium enrichment in the kidneys of *Placopectin magellanicus* exposed to 0.10 g/l ferrochrome lignosulfonate (Liss et al.,1980)

half of the excess for each metal was lost after four days of depuration. When oyster spat (i.e., juveniles) of the species Crassostrea gigas were exposed to this same used mid-weight lignosulfonate drilling fluid, they exhibited soft tissue increases in chromium concentration of two- to threefold in two days, and fourfold after 14 days. Lead concentrations in soft tissue increased twofold after 10 days, while no detectable increase in soft tissue zinc concentrations was noted.

Tornberg et al., (1980) exposed arctic amphipods to mixtures of used, freshwater XC-polymer drilling fluids (5 to 20 percent by volume) and water. The greatest uptake in the ten percent mixture occurred for cadmium, chromium, and lead, and in the five percent mixture for zinc. Maximum uptake relative to control organisms was fivefold for cadmium, and twofold for chromium, lead, and zinc.

A field study of bioaccumulation in organisms around a drilling operation on the mid-Atlantic OCS analyzed tissue data from brittle stars, polychaetes, and molluscs. Based on discharge and sediment analyses, the only metals exhibiting elevated tissue concentrations that were attributed to drilling discharges were barium and chromium (EG&G, 1982). Barium concentrations increased significantly from pre-drilling levels in polychaetes and brittle stars during the first post-drilling survey (two weeks after the completion of drilling activity); molluscs did not accumulate barium to an appreciable degree.

Barium tissue concentrations in polychaetes increased from 23.5 to 87.8 µg/g. Although, the highest tissue levels were found in the immediate vicinity of the well, levels as high as

206 µg/g were found at stations one mile away. Barium concentrations in brittle stars increased from an average tissue concentration of 15.2 ug/g to 217.8 µg/g. Tissue levels were as high as 372 µg/g at one mile stations. Barium tissue levels dropped to pre-drilling levels at all stations after one year (second post-drilling survey).

Regarding chromium, the report (EG&G, 1982) noted that "chromium concentrations in molluscs were generally within the range observed during the pre-drilling cruise." However, this range appears to utilize a single maximum value of 137.2 µg/g (Station 14) which was six times higher than the next highest observed value. This observation for chromium at Station 14 may have been influenced by a second well in the vicinity which the authors point out had been drilled less than a year earlier. Excluding this single outlier drops the pre-drilling mean concentration from 12.9 µg/g to 6.7 µg/g, with the result that chromium concentrations in molluscs during both post-drilling cruises exceed the range observed during the pre-drilling cruise.

Average chromium concentrations in mollusc tissues increased from 6.71 µg/g to 18.5 µg/g to 31.7 µg/g over the three cruises. Average chromium concentrations in polychaete and brittle star tissues changed from 2.28 µg/g to 11.2 µg/g to 41.0 µg/g and 1.49 µg/g to 1.12 µg/g to 2.87 µg/g, respectively. The continued increase in tissue chromium levels of all organisms over a year's time (post-drilling I to post-drilling II) indicates possible continued bioaccumulation of chromium from the low levels in the sediments. EPA (1980) reports bioconcentration factors for marine organisms of from 125 to 200 for hexavalent chromium and from 86 to 153 for trivalent chromium.

Carr et al., (1982) exposed five marine species representing three animal phyla (Arthropoda, Annelida, and Mollusca) to three fractions of a used lignosulfonate drilling fluid. The organisms showed an apparent ability to accumulate chromium from the three mud fractions. In all but two cases, chromium levels fell to pre-exposure levels during depuration. However, marsh clams (Rangia cuneata) and sandworms (Neanthes virens) accumulated chromium to levels two times that of the controls and retained a large fraction of the chromium for an extended period of time.

Brannon and Rao (1979) exposed grass shrimp (Palaemonetes pugio) to 5 mg/liter and 500 mg/liter mixtures of barite in a flow-through seawater system. They analyzed for barium in the carapace (hard tissue), hepatopancreas, and abdominal muscle (soft tissues). Barite is highly insoluble in seawater and some fraction of this particulate material settled to the bottom of the test container. Water samples from the media containing 5 and 50 mg barite per liter had barium concentrations in the water column of 135 µg/liter and 267 µg/liter, respectively. The high barium concentrations were apparently due to particulate matter that remained in suspension rather than due to dissolved barium. Chow (1976) reported a theoretical maximum of 46 µg/l for barium in seawater.

The researchers found that the shrimp exposed to barite accumulated higher barium levels in their exoskeletal and soft tissues than control shrimp in seawater, and that the level of accumulation increased with increasing duration of exposure. Cast off exuviae from the first through the fourth ecdysis, for example, were found to contain 4,392; 13,240; 16,037; and

19,987 mg/kg barium, respectively. Ingestion of settled barite alone could not account for the increased body burdens observed; elevated levels of soluble and/or suspended particulate barite is the most likely cause (T. Duke, EPA, from K. R. Rao, U. West Florida, to R. Cole, Dalton'Dalton' Newport, personal communication, 1983).

Brannon and Rao also noted shrimp ingesting particulate barite and eliminating it in fecal pellets. This could affect fecal pellet nutritional value and sinking rate, which has ecological significance because fecal pellets are important in energy flow and nutrient cycling. Shrimp exposed to barite, in the presence of adequate strontium and calcium in the test water, were found to discriminate for barium and strontium relative to calcium in the hepatopancreas and abdominal muscle. This selective incorporation of barium into soft tissues may provide a long-term opportunity for barium to enter the food chain.

Shrimp were found to discriminate for barium and against strontium relative to calcium in the exoskeleton. This changed the relative mineral composition of cast exoskeletons of grass shrimp from calcium > strontium > barium for control organisms to calcium > barium > strontium for experimental organisms. Incorporation of trace metals into hard tissue can result in removal from the water column that is more long-term than soft tissue incorporation. Although these removal processes may not have toxic implications, they are pathways by which metals are removed from the environment.

Chow and Snyder (1980) studied barium distribution in hard tissues of marine invertebrates collected from the southern California coast, and found that barium concentrations in calcareous exoskeletons were related to the type of organism. Chitons (Nuttalina and Mopalia) averaged 7.4 ppm, mussel (Mytilus) averaged 1.2 ppm, and gastropods (Haliotis and Tegula) averaged 0.8 and 0.5 ppm, respectively. The plates of a barnacle (Balanus) had barium concentrations of 14 ppm, hard tissue of a sea urchin (Strongylocentrotus) had 22 ppm, and corals (species unknown) displayed the highest concentration at 41 ppm.

Barium concentration was related to the mineralogical structure of the skeleton. Calcite skeletons of gastropods are composed of a crystal lattice that does not allow inclusion of the larger barium ion, whereas aragonite skeletons of mussels form a larger lattice structure which does allow for barium incorporation. Skeletons that incorporate other chemical compounds in carbonate form, such as those of the barnacle and sea urchin, allow still higher barium concentrations in skeletons.

For soft tissues, Chow and Snyder (1980) found the average barium concentration in gills, muscles, and gonads was less than one ppm with the exception of the Mytilus specimens. The barium concentration of their stomachs (with contents) showed a wide range of from 0.57 ppm to 108 ppm. This indicates that the digestive tract may be the route of barium entry for some marine organisms. The standard deviation of barium content in various organs of Mytilus exhibited the following trend; stomach > gills > muscles > gonads > shells. This trend supports the hypothesis that the digestive tract is the route of barium entry. The trend also indicates that marine organisms have some degree of regulation over the incorporation of barium into their tissues.

Conklin et al., (1980) note that the mechanisms of barium accumulation are poorly understood. There is some evidence that barium transport is mediated by a divalent-cation-activated adenosinetriphosphate (ATP) transport carrier as well as by micropinocytotic activity of the digestive epithelium. The latter hypothesis is supported by observations that grass shrimp, juvenile lobsters, and meiobenthic nematodes ingest particulate barite and accumulate it in their exoskeletons (Brannon and Rao, 1979; Conklin et al., 1980; Chow and Snyder, 1980).

Many crustaceans have long been known to incorporate granular materials into their statocysts (organs of balance). The granular materials are cemented together by glandular secretions of the statocyst wall to form statoliths. The ectodermal inner chitinous lining and contents of the statocysts (fluid, sensory hairs, and statoliths) are cast off during molting and renewed. Chow et al., (1980) confirmed that grass shrimp may incorporate sand grains, barite particles, or drilling mud particles into their statocysts as they renew the exoskeleton following a molt. The effects on the grass shrimp of this barite incorporation remains to be investigated.

Laboratory data on metal accumulation have been summarized by Petrazzuolo (1983a) in Table 3-19. Exposure to drilling fluids or drilling fluid components has resulted in the accumulation of barium, cadmium, chromium, lead, strontium, and zinc. One metal for which laboratory bioaccumulation data were conspicuous by their absence was mercury.

Maximal observed enrichment factors (tissue levels in exposed animals compared to control animal tissue levels) generally were low (1.6- to 3.4-fold), with the exception of

TABLE 3-19 SUMMARY OF METAL BIOACCUMULATION STUDY RESULTS

Test Organism	Test Substance (Concentration, ppm)	Exposure Period (days)	Depuration Period (days)	Metals, Enrichment Factor[a]								Ref.[b]
				Ba	Ca	Cd	Cr	Cu	Pb	Sr	Zn	
Onisimus sp., Boekosimus sp.	XC-polymer-Unical fluid	20 static	0									1
Whole Animal not gutted	(50,000)					3.2	1.2		2.0		1.6	
	(100,000)					6.4	1.8		2.2		1.3	
	(200,000)					6.0	1.4		1.5		1.5	
Palaemonetes pugio	Barite	7, 48-hour replacement										2
Whole Animal not gutted	5		—	150						1.3		
	50	"	—	350						1.9		
	5	"	14	2.2						1.8		
	50	"	14	29						2.2		
	Barite											
Carapace	500	8 days post-ecdysis, (48-hour replacement)	0	7.7						1.2–2.5		
Hepatopancreas	500			13						1.9–2.8		
Abdominal muscle	500			12						1.5–2.8		
	Barite	106	0									
Carapace	500			60–100	0.07					1.6–7.4		
Hepatopancreas	500			70–300	1					0.03		
Abdominal Muscle	500			50–120	1					0.71		

Adapted from Petrazzuolo (1983a).

TABLE 3-19 SUMMARY OF METAL BIOACCUMULATION STUDY RESULTS
(Continued)

Test Organism	Test Substance (Concentration, ppm)	Exposure Period (days)	Depuration Period (days)	Metals, Enrichment Factor[a]								Ref.[b]
				Ba	Ca	Cd	Cr	Cu	Pb	Sr	Zn	
Mytilus edulis (soft tissue)	12.7 lb/gal lignosulfonate fluid, MAF (Cr = 1.4 ppm)	7	—				6.6					3
	ferrochrome lignosulfonate (Cr = 0.7 ppm)						13					
	(Cr = 6.0 ppm)						64					
	$CrCl_3$ (Cr = 0.6 ppm)						50					
Rangea cuneata (soft tissue)	12.7 lb/gal lignosulfonate fluid, MAF (50,000)	4, static	—				1.4		1.7			4
			4				1.1		1.2			
	13.4 lb/gal lignosulfonate fluid (100,000 MAF)	16, static					2.5					
		—	1				1.7					
		—	14				1.6					
	(layered solid phase)	4, daily replacement	—				4.3					
			1				2.0					

TABLE 3-19 SUMMARY OF METAL ACCUMULATION STUDY RESULTS
(Continued)

Test Organism	Test Substance (Concentration, ppm)	Exposure Period (days)	Depuration Period (days)	Metals, Enrichment Factor[a]								Ref.[b]
				Ba	Ca	Cd	Cr	Cu	Pb	Sr	Zn	
Crassostrea-gigas (soft tissue)	9.2 lb/gal spud fluid (40,000 MAF)	10, static	0						2.1		1.1	
	(10,000 SPP)	4, 24,hour replacement	0				2.5					
	(20,000 SPP)	"	0				3.0					
	(40,000 SPP)	"	0				3.0					
	(60,000 SPP)	"	0				5.5					
	(80,000 SPP)	"	0				7.4					
	12:7 lb/gal lignosulfonate fluid (40,000 MAF)	10, static	0						2.3		1.4	
	(20,000 MAF)	14	0				2.9					
	(40,000 MAF)	14	0				3.9					
	(10,000 MAF)	4, 24-hour replacement	0				2.2					
	(20,000 SPP)	"	0				4.4					
	(40,000 SPP)	"	0				8.6					
	(60,000 SPP)	"	0				24					
	(80,000 SPP)	"	0				36					

TABLE 3-19 SUMMARY OF METAL BIOACCUMULATION STUDY RESULTS (Continued)

Test Organism	Test Substance (Concentration, ppm)	Exposure Period (days)	Depuration Period (days)	Metals, Enrichment Factor[a] Ba	Ca	Cd	Cr	Cu	Pb	Sr	Zn	Ref.[b]
Crassostrea gigas (soft tissue) (Cont.)	17.4 lb/gal lignosulfonate fluid (40,000 MAF)	10, static	0						0.56		1.0	
	(20,000 MAF)	14	0				2.1					
	(40,000 MAF)	14	0				2.2					
Placopecten magellanicus	Uncirculated lignosulfonate fluid											
Kidney	(1,000)	28	0	8.8			2.6					
Adductor	(1,000)	28	0	10			1.2					
	Low density lignosulfonate fluid											
Kidney	(1,000)	14	—				1.6					
		27	—				2.1					
Adductor	(1,000)	—	15				2.3					
		14	—				2					
		27	—				2					
		—	15				2					
	FCLS (30)	14	—				5.7					
		—	14				3.2					
	(100)	14	—				6.0					
		—	14				5.2					
	(1,000)	14	—				7.2					
		—	14				6.0					

TABLE 3-19 SUMMARY OF METAL ACCUMULATION STUDY RESULTS
(Continued)

Test Organism	Test Substance (Concentration, ppm)	Exposure Period (days)	Depuration Period (days)	Metals, Enrichment Factor[a]								Ref.[b]
				Ba	Ca	Cd	Cr	Cu	Pb	Sr	Zn	
Myoxocephalus quadricornis (gutted)	XC-polymer fluid	36, 48-hour replacement									6	
	(5,000)						3.3	1.1	1.25		1.2	
	(10,000)						2.9	3.1	1.7		1.2	

[a] Enrichment Factor = Concentration in exposed group/concentration in controls.

[b] References:
1. Tornberg et al., (1980).
2. Brannon and Rao (1979).
3. Page et al., (1980).
4. McCulloch et al., (1980).
5. Liss et al., (1980).
6. Sohio Alaska Petroleum Company (1981).

Abbreviations:
MAF - mud aqueous fraction
SPP - suspended particulate phase
FCLS - ferrochrome lignosulfonate

barium (300-fold) and chromium (36-fold). Although functional changes resulting from metal accumulation were not explicitly addressed in these studies, no gross, overt functional changes or potential alterations have been noted.

The ability of exposed animals to clear metals accumulated during exposure to drilling fluids or components also have been reported. These data are summarized (Petrazzuolo, 1983a) in Table 3-20. Depuration studies suggest that a substantial release of barium, chromium, lead, and strontium may occur. For whole animal, soft tissue, and muscle tissue analyses, 40-90 percent of the excess metal (barium, lead, chromium, and strontium) that was accumulated following 4- to 28-day exposures was released during 1- to 14-day depuration periods. Possibly, length of exposure and extent of depuration are inversely related. Transient increases were observed in chromium, lead, and strontium levels during the depuration period. The only sustained increase (48 percent) during this period occurred in chromium in scallop kidney. This finding is somewhat confounded by a similar trend (+24 percent) in control animals.

These data suggested that bioaccumulation of metals as a result of drilling fluids discharges did not appear to be a significant problem. Yet, three factors argued against this conclusion. Instead, Petrazzuolo (1983a) assessed bioaccumulation as a significant unknown. First, uptake kinetics were not adequately described, largely attributable to the rather short exposure periods. These exposures were most often for 14 days or less.

TABLE 3-20 DEPURATION OF METALS BIOACCUMULATED DURING EXPOSURE TO DRILLING FLUIDS OR COMPONENTS[a]

Test Species	Test Substance	Exposure Period (days)	Metal	Tissue	Depuration Level[b]	Depuration Period (days)
Palaemonetes pugio	$BaSO_4$	7	Ba	whole animal, not gutted	-90%	7
"	"		Sr	"	-90%	7
Rangia cuneata	SLF[c] (LSP)	1-4	Cr	soft tissue	-(40-65%)	1
	MDLF (MAF)	4	Cr	"	-75%	4
		"	Pb	"	-70%	4
	SLF (MAF)	16	Cr	"	-53%	1
		"	"		-60%	3-14
Placopectan magellanicus	LDLF (WM)	27	Cr	kidney	+48%[d]	14
	"	"	Cr	adductor muscle	-63%	14
	FCLS	14	Cr	kidney	-(17-54%)	14

Adapted from Petrazzuolo (1983a).

[a] Adapted from Brannon and Rao (1979); McCulloch et al. (1980), Liss et al. (1980).

[b] Percentage of excess metal released.

[c] Abbreviations: SLF, MDLF, LDLF (seawater, medium density, and low density lignosulfonate fluids), FCLS (ferrochrome lignosulfonate), MAF, WM (mud aqueous fraction, whole fluid).

[d] Control animals exhibited a 24% increase during the depuration period.

Occasionally 16- to 28-day exposures occurred; in one case, a 106-day exposure occurred but with only one intermediate value reported.

The available data do not allow for any firm conclusions about the extent of potential uptake. Simple saturation kinetics occur for several metals and species. However, complex saturation kinetics also occur frequently. The long-term study with 106-day exposure did not report adequate data to characterize uptake kinetics. Since metals are highly persistent, long-term accumulation potential must be assessed.

Second, the focus of these studies was often diffuse. Bioaccumulation studies should identify which of two toxicologic problems is being addressed: (1) human health impacts (edible tissue analyses) or (2) marine organism impacts (target organ analyses). Functional studies must be undertaken to link accumulation to adverse physiological/biochemical responses.

Third, exposure levels were difficult to quantify in a meaningful way for correlation to field exposure conditions. The assessment of the bioaccumulation of drilling fluids-related metals will be driven by the exposure of benthic epifauna and infauna to drilling fluid particulates. Yet, bioaccumulation studies routinely have tested whole fluids or the aqueous phase of fluids. These exposures could have either over-estimated or under-estimated potential accumulation. Furthermore, in those studies that have tested solid phase material, accumulation was only measured in response to a deposit layer. Therefore, no concentration-effect relationship can be constructed that could estimate uptake from anything but a 100 percent exposure situation. This design does not lend itself to a meaningful quantitative assessment.

A more recent report by Neff et al., (1984) examined uptake of barium and chromium from the liquid settleable phase of drilling muds. Experiments included several species of invertebrates; clams, worms, shrimp, scallops, lobsters, and one fish (flounder). Lobsters and flounder were fed contaminated and depurated worms to test for food chain transfer or magnification. These experiments were performed for longer periods of time (56 to 119 days) than previous tests. Maximum bioenrichment factors for barium and chromium were in the range of 2.6 to 16.8 for barium and 1.9 to 2.8 for chromium. These results are consistent with previous tests.

The design of these experiments was intended to simulate more realistic field conditions. However, the bioaccumulation and bioenrichment values are compromised both by the variability of the data and, more importantly, by the fact that sediment barium and chromium levels decreased dramatically during the course of each experiment (40-80 percent for barium, 25-60 percent for chromium). Thus, assessing exposure in these experiments is very difficult and extrapolation to field conditions, in which concentrations increase during drilling, is confounded by this experimental design, not simplified.

In summary, Petrazzuolo (1983a) evaluated bioaccumulation data for drilling fluids and components and concluded the following:

(1) Several metals can be accumulated, including barium, cadmium, chromium, lead, strontium, and zinc. Mercury is conspicuous by the absence of any laboratory uptake data.

(2) In terms of results, observations that militate against any significant potential for adverse effects are: enrichment factors are generally low (barium and chromium excluded), depuration release levels are high, and no gross functional alterations, resulting from metal accumulation following high exposures to drilling fluids or components, have been reported.

(3) Such a conclusion is largely compromised by several other observations. Test results indicate that uptake kinetics are not simple, with saturation plateaus beyond the scope and predictive power of studies that have been conducted. Test design problems also contribute to equivocal interpretations and to poor utility in hazard assessment analyses. These design problems include: the choice of inappropriate drilling fluid fractions as test substances; the use of only one effective exposure concentration for fluid solids exposures; and the choice of tissues for analyses that are inappropriate for the species.

(4) Because of (a) the extreme persistence of metals, (b) the elevation of sediment metal levels resulting from drilling discharges, (c) the notable toxicity of some of the metals examined (cadmium and lead), (d) the absence of laboratory data on a significantly toxic metals (mercury), and (e) the inability to estimate potential effects from environmentally realistic exposures, metal accumulation should be considered an important area requiring further study.

3.5.1.2 Bioaccumulation of Hydrocarbons from Produced Water

There is evidence that hydrocarbons, discharged with produced water, are bioaccumulated by various marine organisms. In the Central Gulf of Mexico study (Nulton et al., 1981) analyses revealed the presence of low levels of alkylated benzenes, naphthalene, alkylated naphthalenes, phenanthrene, alkylated three-ring aromatics, and pyrene in a variety of fish and epifauna. Isomer distributions of alkylated benzenes and naphthalenes were similar to those seen in crude oil.

Middleditch (1980) analyzed hydrocarbons in tissues of organisms in the Buccaneer Field. During the first two years of the study, tissue from barnacles from the platform fouling community at depths ~ 3 m from the surface contained up to 4 ppm petroleum alkanes. Middleditch claims that biodegradation of petroleum hydrocarbons in the barnacles was apparently efficient. Analyses of the fouling mat on the platform revealed that most samples contained petroleum hydrocarbons, and concentrations were particularly high in those collected just below the air/sea surface.

Middleditch (1980) found petroleum hydrocarbons in 15 of 31 fish species examined around the Buccaneer Field Platform. They focused their analyses on four of the species--crested blenny, sheepshead, spadefish, and red snapper. Virtually every specimen of crested blenny examined contained petroleum alkanes. In this species, the n-octadecane/phytane ratio was similar to that of produced water but the n-heptadecane/pristane ratio is distorted by the presence of endogenous pristane of biogenic origin. The mean alkane concentration in this species was 6.8 ppm. This species feeds on the platform fouling community, and it was suggested that this food was the source of petroleum hydrocarbons to the fish.

Similar results were obtained with sheepshead, which also partially feeds on the platform community. Petroleum alkanes were found in about half of the muscle samples and in about one quarter of the liver samples. The mean alkane concentrations in these tissues were 4.6 and 6.1 ppm, respectively.

Spadefish exhibited lower concentrations of alkanes in muscle and liver (0.6 and 2.0 ppm), and this species does not utilize the platform fouling community as a food source to the same extent as the two previously described species. Lower levels of alkanes were also observed in red snapper (1.3 ppm in muscle, and 1.1 ppm in livers).

With one exception, most shrimp analyzed by Middleditch did not contain alkanes. This probably reflects the highly migratory behavior of these animals. Similarly, the petroleum hydrocarbons were not found in white squid.

Middleditch also examined nine benthic organisms for petroleum hydrocarbons. Yellow corals (Alcyonarians) contained alkanes but Middleditch suggested these could be of biogenic origin. Various hydrocarbon profiles were observed in species. Few of the specimens of winged oyster (Pteria colymbus) contained petroleum alkanes while they did contain methylnaphthalenes and benzo[a]pyrene.

3.5.2 Biomagnification

Bioaccumulation relates to contaminant accumulation in a single species. If the contaminant is passed from prey to predator on to the next trophic level, a net increase in pollutant body burden up the food chain can result, and is known as biomagnification. Biomagnification is difficult to test experimentally and is generally assessed by comparing body burdens between organisms at different trophic levels.

Little information is available to allow an assessment of biomagnification of the components of drilling fluid or produced water discharges. Studies have been examined, however, which assessed biomagnification of other inorganic and organic pollutants in various food chains.

In an experiment to evaluate food chain transfer, sand worms were fed to flounder and lobsters, including worms that had been contaminated by living on barium-rich sediments and those which had been subsequently depurated (Neff et al., 1984).

The mean barium level in contaminated worms was 22 µg/g, whereas the controls contained 7.1 µg/g. Chromium levels were 1.02 µg/g in contaminated worms and 0.62 µg/g in controls. In both cases depurated worms were not significantly different from controls.

The mean enrichment in muscle barium concentration was 7.2-fold. Flounder fed contaminated food while living on uncontaminated sediment did not accumulate barium in muscle tissue. There was no significant uptake of chromium.

Type of food had no effect on mean barium concentrations in tail muscle of lobsters exposed to uncontaminated sediments. Lobsters living on contaminated sediments accumulated barium in muscle tissue when fed either uncontaminated or contaminated food.

The above data suggests that contact with sediments may be more important in the bioaccumulation of barium than direct food transfer. Throughout these experiments the metal content of food was highly variable. Animals may have gone through periods of uptake and depuration relative to this food and also the sediment on which they were living. Because of the timing of analyses on food (weekly) versus animals (at 56 days and 99 days), it is not possible to develop any direct relationship between food source and animal tissue concentrations.

Studies of DDT and PCB organochlorine compounds reveal that accumulation of these compounds in the tissues of fish, mammals, and birds from prey to predator occurs. Moreover, lipid concentrations show an increase with trophic level which indicates that dietary uptake and subsequent biomagnification is taking place. Studies undertaken with fish provide clear evidence that organochlorine uptake occurs more rapidly than does elimination, leading to increasing pollutant burdens with time and selective tissue accumulation at higher trophic levels (Fowler, 1982). However, for species at lower trophic levels such processes are less clear.

Fowler (1982) cites several studies analyzing specific food chains for organochlorine biomagnification with mixed results. It was suggested that these studies failed because they assumed the primary organochlorine input was through the food chain, whereas recent studies indicate the water column may be the primary source, at least for zooplankton. Fowler speculates that plankton and small invertebrates accumulate substantial amounts of material from the surrounding water, and will reflect its composition more strongly than vertebrates, which are generally larger and have less surface area for absorption and therefore are more likely to accumulate most of their organochlorines from prey consumed.

Data presented from California (Schafer et al., 1982) concern trace metal and organic compound contamination in the marine environment. They examined three different food chains in California and found increasing concentrations of DDT and PCB with trophic level, but no evidence of increasing metal concentrations except for organic mercury, which had a very strong increase.

Most data on inorganic pollutant biomagnification show a decrease in trace metal and radionuclide burden with higher trophic level. However, there are exceptions found in specific food chains. Dog whelks were found to have three times more cadmium and four times more zinc than the limpets they consumed (Pedan et al., 1973, as in Fowler, 1982), and subsequent depuration experiments showed the whelks retained these metals. However, other experimental results have shown that whelks did not magnify zinc or iron in contaminated barnacles upon which they were fed.

One qualification for much of the metal data, however, is that muscle tissues were the most frequently sampled and analyzed. These tissues are not known to be physiological sinks for metal contaminants. No data have been identified that address target organ sites, such as hepatopancreas or kidney tissues, which would be the functional analogs to organic contaminants in fat and muscle tissue. Thus, the apparent difference between organics and metals may be due to the choice of tissue analyzed.

Cesium-137 has been shown by Fowler (1982) to accumulate in higher trophic level fish in the food chain, and he concluded that, "...the high degree of assimilation... from prey results in an overall accumulation up the food chain." Studies examining plutonium-237 also indicated biomagnification. However, more recent work has shown that the implicated organisms (starfish) rapidly absorb plutonium from the water and eliminate it slowly. This further indicates the importance of knowing the uptake pathways prior to making conclusions regarding biomagnification.

Studies assessing biomagnification of petroleum hydrocarbons are more limited than for other pollutants, but the few data available suggest that these contaminants are not subject to biomagnification. One reason for this observation is that the primary source of these compounds for organisms may be absorption from the water column rather than ingestion. Also, biological half-times of some petroleum hydrocarbons may be short, with many species purging themselves within a few days. Middleditch (1980), in studying the fouling community and associated pelagic fish, found that many species were contaminated with hydrocarbons discharged in produced water.

3.5.3 Ingestion and Excretion

Organisms also remove material from suspension through ingestion of suspended particulate matter and excretion of this material in fecal pellets. These larger pellets exhibit different transport characteristics than the original smaller particles. Houghton et al., (1981) note that filter feeding plankton and other organisms ingest fine suspended solids (1 µm to 50 µm) and excrete large fecal pellets (30 µm to 3,000 µm) with a settling velocity typical of coarse silt or fine sand grains. They also note that copepods are important in forming aggregate particles.

Zooplankton have been found to play a major role in transporting metals and petroleum hydrocarbons from the upper water levels to the sea bottom (Hall et al., 1978). The largest fraction of ingested metals moves through the animal with the unassimilated food and passes out with the fecal pellets in a more concentrated state (Fowler, 1982). Zooplankton fecal pellets have also been found to contain high concentrations of petroleum oil, especially those of barnacle larvae and copepods. Hall et al., (1978) calculate that a population of calanoid copepods grazing on an oil slick could transport three tons of oil per square kilometer per day to the bottom.

3.5.4 Sediment Reworking

Another pathway of biological removal of pollutants involves benthic organisms reworking sediment and mixing surface material into deeper sediment layers. This process is known as bioturbation, and moves barite and clays from drilling mud to greater depths than they would otherwise achieve. Bioturbation can also expose previously buried material, and could be an important factor in potential long-term impacts. No work was found to quantify bioturbation effects, although a few studies have observed organisms living on a cuttings pile

or in the vicinity of drilling discharges (Menzie et al., 1980; Ayers et al., 1980b). However, if the environment is one which rapidly removes cuttings piles, or where physical forces dominate resuspension and reworking processes, then biological mixing activities may not prove significant.

4.0 TOXICITY TESTING

4.1 SUMMARY

4.1.1 Drilling Fluids

The toxicity of drilling fluids and drilling fluid components has been tested through laboratory tests using single species and microcosm experiments. These were either "acute" (short-term) tests in which the concentration that produces 50 percent mortality in a given test species commonly is determined or "chronic" (long-term) tests in which the effect on survivability, growth, maturation, or reproduction is assessed. Drilling mud toxicity tests have been performed using whole muds or various component fractions, such as the suspended particulate phase or mud aqueous fraction. Proposed guidelines for suspended particulate phase toxicity testing have been developed by EPA. The extrapolation of single species tests to overall effects in the ecosystem still has a large, inherent uncertainty.

Acute or short-term tests have generally indicated low toxicity. In a summary of over 415 toxicity tests of 68 muds using 70 species, 1-2 percent of the tests exhibited LC_{50}'s ranging from 100 to 999 ppm, 6 percent exhibited LC_{50}'s ranging from 1,000 to 10,000 ppm, 46 percent exhibited LC_{50}'s ranging from 10,000 to 100,000 ppm, and 44 percent exhibited LC_{50}'s greater than 100,000 ppm. Two to three percent of the data were not usable. A significant difference was noted between the toxicity of generic muds, which appear to have acute, lethal toxicity characteristics similar to the distribution of the larger data set described above, and a series of 11 nongeneric muds provided to EPA by the Petroleum

Equipment Supplies Association. These latter muds, as a group, appear to be substantially more toxic than would be anticipated from the toxicity distribution of either the generic muds or the larger data set. Whole muds appear to be more toxic than aqueous or particulate fractions. The suspended particulate phase appears to be more toxic than the other individual phases. One author has ranked organisms according to their sensitivity to drilling fluids in tests and found the following order of decreasing sensitivity: copepods and other plankton, shrimp, lobsters, mysids and finfish, bivalves, crabs, amphipods, echinoderms, gastropods, and polychaetes and isopods. Larval organisms are more sensitive than adult stages (maximally 20-fold); animals are more susceptible during molting.

Acute sublethal effects using a sensitive test species and very toxic muds showed a low potential for sublethal effects, with swimming behavior commensurately affected at concentrations approximately three-fold lower than mortality. However, swimming behavior is not a particularly sensitive sublethal indicator.

In another series of tests, the addition of mineral oil at 5 percent by volume produced burrowing impairment in two species of invertebrates (softshell clam, sandworm). The same sublethal responses were seen with the addition of 0.5 percent low-sulfur or high-sulfur diesel fuel. Several species, (shrimp, fish, scallops) have also been observed to exhibit strong avoidance responses upon initial exposure to the settleable fraction of water-based drilling muds.

Chronic or long-term toxicity tests performed on corals include cleaning rates, polyp retraction, mucus secretion, zooxanthellae expulsion, and growth rates. The effect of drilling muds on swimming rates in larval crabs, molting rates and shelter construction time in lobster have also been assessed.

The data base on chronic lethal effects is far smaller than that on acute lethality; chronic lethal tests number only six, compared to more than 400 acute lethal tests. The few chronic data are consistent, however, and indicate that chronic lethal toxicity is not likely to be more than some 20-fold greater than acute lethal toxicity.

Chronic sublethal toxicity has been more extensively studied than chronic lethal toxicity. Chronic sublethal toxicity appears to range from three-fold to 75-fold greater than acute lethal toxicity, and thus is within the same range as chronic lethal effects. However, these sublethal data are much more difficult to interpret. Toxicity end points are difficult to interpret, physiologically and ecologically. Sample sizes routinely are very small. Most importantly, observations that sublethal effects occur "close" to lethal effect levels miss the point; for most studies changes were also noted at the lowest level tested. Thus, estimating No-Observable-Effect-Levels is not possible for much of the reported data.

Laboratory studies on recruitment and development of benthic communities suggest that drilling mud and barite can affect recruitmemt and alter benthic communities or depress abundances. These data are corroborated by results from artificial substrate experiments conducted in the Beaufort Sea; these showed significantly different colonization rates at drilling fluid test plots and control plots, especially for amphipods and copepods.

Muds are complex mixtures and there appears to be no single explanation for toxicity. Some of the apparent (actual) toxicity may be due to physical effects, such as particle size coagulations, abrasions, etc. These are, however, a form of toxicity, producing and contributing, in part or in combination with chemical toxicity, to the end points (death) in acute toxicity tests.

Oxygen demand appears strongly correlated with toxicity in laboratory toxicity tests. Spearman Rank correlations of 96 hour LC_{50} data and BOD/UOD data showed a remarkably strong correlation, especially with BOD_5 data derived with artificial seawater and activated seed. These data showed a correlation of 0.97 with toxicity. All BOD/UOD values showed correlations of 0.87 to 0.97 (BOD) and 0.91 to 0.95 (UOD), but TOC/COD values gave correlations of 0.64 to 0.67. Given the absence of oxygen demand data, no such correlation could be developed for nongeneric muds. Another indicator of the large inherent oxygen demand of drilling muds is that dissolved oxygen levels in test environments dropped below normal, notwithstanding the continuous aeration of test media that followed pre-aeration of the test material. This was especially noted during the first day of testing, during which dissolved oxygen levels were depressed concentration--dependently by the test muds.

Studies have found high correlations (diesel oil $r=0.88$; mineral oil $r=0.97$) of toxicity with added (diesel/mineral) oil to whole mud. Toxicity did not correlate quite as well with the oil levels determined in a variety of mud samples (r=0.81). The available data indicate that this may be partially due to various types of sequestrations within the drilling fluid matrix as well as the variable presence of toxic constituents in drilling fluids other than diesel or mineral oil.

The variability and complexity in the composition of muds is reflected in the results and interpretation of toxicity tests. Test results of sample splits of the same mud performed at two different laboratories have differed by an order of magnitude. In such cases, laboratory procedure or sample handling is a significant factor. Different batches of the same generic mud have shown significantly different toxicities. In this case different proportions of major constituents (as allowed by mud type definition) may be a factor. EPA has attempted to improve consistency in toxicity test results by recommending standard procedures for sample handling and testing. In recent interlaboratory tests on the same batch of mud, consistent test results were obtained.

4.1.2 Produced Water

Available data on produced water acute lethal toxicity indicates that these discharges are not particularly toxic. However, several qualifications are required. Limited data on 96-hr LC_{50} values for produced waters that did not contain measurable biocides were observed to range between 8,000 and 408,000 ppm for one series of tests. The LC_{50} values are similar to those obtained for the water soluble fractions of crude oils (140,000 - 430,000 ppm). While these waste streams have some dissimilarities, both exhibit similar concentrations of light aromatic hydrocarbons and these compounds may be contributing to the acute toxicity. These hydrocarbons may be present partially as micelles, in addition to being dissolved. However, it should be noted that an undetermined amount of toxic compounds are lost from the produced water upon collection, transport to the laboratory, and aeration.

Limited data for produced waters that contain biocides indicate that these chemicals can increase the toxicity of the effluent. LC_{50} values (48- and 96-hour) in the range of 1850-6500 ppm were observed for produced water containing an undetermined amount of the biocides K-31 (glutaraldehyde) and KC-14 (alkyldimethylbenzyl chloride) that were not scavenged. Blennies kept in cages below the produced water discharge pipe of a production platform in the Buccaneer Field suffered no mortalities when the effluent had not been treated with biocide, but approximately half of the blennies died (within 48 hrs) when biocides were present. (The type and concentration of biocide in use was not documented.)

Another report noted that divers experienced eye and skin irritation sufficient to interrupt their activities when working near the produced water discharge from the Buccaneer Field when acrolein was being used as a biocide. As already noted, there are little data on the concentrations of biocides in produced water although a variety of chemicals are used. Over 500 products are currently registered with EPA's Office of Pesticides as biocides in both drilling muds and waterflooding operations.

Although the acute toxic effects of produced water appear to be low (when biocides are absent), chronic lethal and sublethal effects may occur inasmuch as these are generally exhibited at concentrations below those that are acutely toxic. Chronic exposures could occur in the water column in areas experiencing limited flushing and where the input of produced water is continuous. However, hydrocarbons that have become associated with the sediment are a more likely cause of chronic exposure. Because of the continual input from produced water, the sediment hydrocarbon load could include lighter aromatic fractions as well as heavier molecular weight hydrocarbons.

There is ample evidence to indicate that such hydrocarbon accumulation can occur. Field studies at Trinity Bay and Buccaneer Field also suggest that impacts have occurred on the benthic fauna. Chronic sublethal toxicity of produced water could occur at aromatic hydrocarbon levels on the order of 1 μg/l.

4.2 INTRODUCTION

This section presents information on the toxicity of drilling mud and produced water discharges and the specific chemical components of these discharges. The section also considers potential ecological effects of effluents on community recruitment. Toxicity tests are used to determine levels of pollutant concentrations which can cause lethal or sublethal effects on organisms, and are categorized as either acute or chronic. Acute toxicity tests involve exposures of 96 hours or less, while chronic toxicity tests involve long-term exposures, usually entire or partial life cycles.

4.2.1 Acute Toxicity Testing

Acute toxicity tests are used to determine the short-term effects of a chemical or mixture on an organism. Results are generally reported as the concentration at which 50 percent of the organisms are killed (the LC_{50}, or median lethal concentration), or display a defined effect of toxicological importance, such as loss of mobility (the EC_{50} or median effects concentration). The higher the LC_{50} or EC_{50} for a given exposure time, the lower the toxicity of the substance being tested.

Acute toxicity tests can be conducted in static, renewal, or flow-through systems. Static systems involve exposure to a single batch of test solution for the full test period. Renewal systems involve periodically replacing the test solution with new solution of the same concentration. In flow-through systems, the test solution is continuously replaced and excreted metabolites are removed. EPA's proposed protocol for toxicity testing of drilling fluids specifies a static bioassay system (Petrazzuolo, 1984).

4.2.2 Chronic Toxicity Testing

Chronic toxicity tests evaluate the long-term effects of pollutant exposure on survivability, growth, maturation, and reproduction. The results are generally expressed as a range, with the smaller value the lowest concentration resulting in the prescribed effect, and the larger value the highest concentration not producing the effect. EPA (1980j) specifies flow-through system testing protocols for chronic toxicity tests.

Chronic tests can be life cycle, partial life cycle, or early life stage. Life cycle testing exposes organisms from embryo or newly-hatched larval stage through at least 24 hours after the hatching of the next generation. Partial life cycle tests expose organisms through part of the life cycle, and are used in situations where the organism takes a long period (e.g., a year or more) to mature. Early life stage testing focuses on the embryonic stage shortly after fertilization through early juvenile development.

4.3 TOXICITY OF DRILLING FLUIDS

Toxicity testing data are used in impact assessments to estimate the potential for environmental damage, even though uncertainty arises from the extrapolation of single species tests to assessments of overall effects. The scientific interest in potential environmental effects of drilling has prompted many researchers to conduct tests with various drilling muds, drilling mud fractions, and a wide variety of test organisms. The recently proposed EPA protocol for drilling mud toxicity testing is based on EPA Region II bioassay procedures, with certain modifications. This protocol specifies testing of the suspended particulate phase (SPP) of drilling mud, as follows:

- Suspended Particulate Phase (SPP). One part by volume of drilling fluid is added to nine parts seawater. The drilling fluid-seawater slurry is well mixed and the suspension is allowed to settle for one hour before the supernatant SPP is siphoned off. The SPP is mixed for five minutes and then used immediately in bioassays.

There are other drilling mud fractions which have been used in bioassay testing, including:

- Layered Solid Phase (LSP). A known volume of drilling fluid is layered over the bottom of the test vessel or added to seawater in the vessel. Although little or no mixing of the slurry occurs during the test, the water column contains a residual of very fine particulates which do not settle out of solution.

- Suspended Solids Phase (SSP). Known volumes of drilling fluids are added to seawater and the mixture is kept in suspension by aeration or mechanical means.

- Mud Aqueous Fraction (MAF). One part by volume of drilling fluid is added to either four or nine parts seawater. The mixture is stirred thoroughly and then allowed to settle for 20-24 hours. The resulting supernatant MAF is siphoned off for immediate use in bioassays. The MAF is similar to the SPP but has a longer settling time, so the concentration of particulates in the supernatant is lower.

- Filtered Mud Aqueous Fraction (FMAF). The mud aqueous fraction of whole drilling fluid is centrifuged and/or passed through a 0.45μm filter and the resulting solution is the filtered mud aqueous fraction.

Used muds appear to exhibit higher toxicity than new muds, although this question remains controversial. Neff et al., (1981) cite decomposition of organic materials during the drilling process as the probable cause of increased toxicity of used drilling fluids. For example, the high temperature, pressure, and alkalinity characteristic of downhole drilling conditions can decompose chrome lignosulfonate to phenolic compounds such as vanillin and isoeugenol (Carney and Harris, 1975, as cited in Neff et al., 1981). The presence of diesel oil in the used drilling mud has also been shown to contribute to increased toxicity (Conklin et al., 1983; Duke and Parrish, 1984).

4.3.1 Acute Toxicity of Drilling Fluids

Acute toxicity tests of whole drilling fluids have generally produced low toxicity. Petrazzuolo (1983a) summarized the results of 415 such tests of 68 muds in 70 species and found 1 to 2 percent had LC_{50}'s ranging from 100 to 999 ppm, 6 percent had LC_{50}'s ranging from 1,000 to 9,999 ppm, 46 percent had LC_{50}'s ranging from 10,000 to 99,999 ppm, and 44 percent had LC_{50}'s of greater than 100,000 ppm (Table 4-1). The toxicity level nomenclature is that of Hocutt and Stauffer (1980). For purposes of comparison, almost all acute toxicities to marine organisms for EPA's 129 priority pollutants fall into the range from 0.007 ppm to 270 ppm (EPA, 1980a-i).

Test results also indicate that whole drilling fluid is more toxic than the aqueous or particulate fractions (Table 4-2). These data show whole fluid toxicity ranging from one to five times that of the aqueous fraction, and 1.3 times the toxicity of the particulate fraction. Acute toxicity tests for used drilling fluids and drilling fluid components are shown in Table 4-3. Criterion values for drilling fluid fractions in the table are converted to whole fluid equivalents. For example, the MAF is prepared by mixing one part drilling mud

TABLE 4-1 SUMMARY TABLE OF THE ACUTE LETHAL TOXICITY OF DRILLING FLUID

	Number of species tested	Number of fluids tested	Number of tests	Number of 96-hour LC_{50} values (ppm)[a]					
				Not determinable	< 100	100-999	1000-9999	10,000-99,999	>100,000
Phytoplankton	1	9	12	5	0	0	7	0	0
Invertebrates									
Copepods	1	9	11	1	0	3	5	2	0
Iscpods	2	4	6	0	0	0	0	1	5
Amphipods	4	11	22	0	0	0	0	7	15
Gastropods	5	5	10	0	0	0	0	2	8
Decapods									
Shrimp	9	23	66	0	0	6(1)[b]	5	36	19
Crab	8	18	32	1	0	0	3	17	11
Lobster	1	2	7	0	0	0	1	3	3
Bivalves	11	22	59	19[d]	0	0	1	19	20
Echinoderms	2	2	4	0	0	0	0	1	3
Mysids	4	17	64	2(1)[d]	0	0	1	29	32
Annelids	7	14	34	3[d]	0	0	0	12	19
Finfish	15	24	80	0	0	0	2	50	36
TOTALS	48	40[c]	303	31(23)[d]	0	4-9	25	179	171
Percentages as a fraction of the total number of tests	70	68	415 392[e]	2%	0%	2.4% (1%)[b]	6%	46%	44%
Average percentage in a category for each group of animals				5.3%	0%	2.8% (2.1%)[b]	9.4%	33%	50%

Adapted from Petrazzuolo (1983a).

[a] Placement in classes according to LC_{50} value.
Lowest boundary of range if LC_{50} expressed as a range.
Cited values if given as ">" "<". There were 199 such LC_{50} values; 95 were 100,000 ppm; 20 were <3,200 ppm.

[b] These include tests conducted on drilling fluids obtained from Mobile Bay, Alabama, and which may not be representative of drilling fluids used and discharged on the OCS. The value in parenthesis is the result of not including those drilling fluids.

[c] The fluids used in Gerber et al., 1980, Neff et al., 1980, and Carr et al. 1980 were all supplied by API. Their characteristics were very similar and they may have been subsamples of the same fluids. If so, the total number of fluids tested would be 35.

[d] Data not available.

[e] Number of tests with actual data.

TABLE 4-2. COMPARISON OF WHOLE FLUID TOXICITY AND AQUEOUS AND PARTICULATE FRACTION TOXICITY FOR SOME ORGANISMS
(Petrazzuolo, 1981)

Organism	Whole fluid vs. aqueous fraction	Whole fluids vs. particulate fraction
Gammarus (amphipod)	> 1.4 to 3.6:1	
Thais (gastropod)	> 1.2:1	
Crangon (shrimp)	> 1.1 to 1.4:1	
Carcinus (crab)	> 1.1 to 1.5:1	
Homarus (lobster)	> 3.5 to 5.3:1	
Strongylocentrotus (sea urchin)	> 2:1	
Coregonus (whitefish)	< 1.7:1	
Neomysis (shrimp)		1.3:1

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS (96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
		USED DRILLING FLUIDS		
ALGA				
Skeletonema costatum	Imco LDLS/SW	1,325-4,700 (96-h EC50)	4	1
	Imco Lime/SW	1,375 (96-h EC50)	4	1
	Imco non-dispersed/SW	5,700 (96-h EC50)	4	1
	Lightly treated LS/SW-FW	3,700 (96-h EC50)	4	2
COPEPODS				
Acartia tonsa	Imco LDLS/SW	5,300-9,300	4	1
	Imco Lime/SW	5,600	4	1
	Imco non-dispersed/SW	66,500	5	1
	Lightly treated LS/SW-FW	10,000	5	2
	FCLS/FW	100-230	3	2
	Saltwater Gel	100	3	2
ISOPODS				
Gnorimosphaeroma oregonsis	FCLS/FW	70,000	5-6	3
Saduria entomon	XC-Polymer/Unical	314,000-500,000	6	4
	CMC-Resinex Tannathin-Gel	530,000-600,000	6	4
AMPHIPODS				
Anisogammarus confervicolus	FCLS/FW	10,000-50,000	5	3
	FCLS/FW	10,000-200,000 (48-h LC50)	5-6	3
Onisimus sp./*Boekisima* sp.	XC-Polymer/Unical	200,000-436,000	6	4
Gammarus locusta	Spud mud	100,000	6	5
	MDLS	74,000-90,000	5	5
	MDLS (WAF)	100,000	6	5
	HDLS	28,000-88,000	5	5
	HDLS (WAF)	100,000	6	5
GASTROPODS				
Nautica clausa, *Neptuna* sp., & *Buccinum* sp.	CMC-Resinex Tannathin-Gel	600,000-700,000	6	4
Littorina littorea	LDLS (WAF)	100,000	6	5
Thais lapillis	LDLS	83,000	5	5
	LDLS (WAF)	100,000	6	5
	LDLS (suspended WM)	15,000	5	5
	MDLS	100,000	6	5
	MDLS (WAF)	100,000	6	5
	HDLS	100,000	6	5
	HDLS (WAF)	100,000	6	5

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS (96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981) (Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
DECAPODS-SHRIMP				
Artemia salina	FCLS/FW	100,000 (48-h LC50)	6	3
Pandalus hypsinotus	FCLS/FW	32,000-150,000	5-6	3
		50,000-100,000 (48-h LC50)	5	3
Crangon septemspinosa	Spud mud (MAF)	100,000	6	5
	Seawater LS (MAF)	100,000	6	5
	LDLS	71,000	5	5
	LDLS (suspended WM)	15,000	5	5
	LDLS (MAF)	98,000-100,000	5	5
	MDLS	82,000	5	5
	MDLS (suspended WM)	15,000	5	5
	MDLS (MAF)	17,000	5	5
	MDLS (FMAF)	19,000	5	5
	HDLS	92,000	5	5
	HDLS (suspended WM)	15,000	5	5
	HDLS (MAF)	100,000	6	5
	HDLS (FMAF)	100,000	6	5
Pandalus borealis	HDLS (MAF)	65,000	5	5
Stage I larvae	HDLS (FMAF)	55,000	5	5
Palaemonetes pugio	Spud mud (MAF)	100,000	6	6
Stage I zoeae	Seawater-chrome LS (MAF)	27,500	5	6
	MDLS (MAF)	35,000	5	6
	HDLS (MAF)	18,000	5	6
	HDLS (SPP)	11,800	5	6
Adults	Spud mud (MAF)	100,000	6	6
	Seawater-chrome LS (MAF)	92,400	5	6
	MDLS (MAF)	91,000	5	6
	HDLS (MAF)	100,000	6	6
	Lightly treated LS	201	3	11
Stage III zoeae	HDLS (SPP)	11,700-13,200	5	6
Late premolt stage	Mobile Bay fluid	318-863	3	7
D_2 - D_4	Mobile Bay fluid	360-14,560	3-5	9
Palaemonetes pugio				
larvae	Seawater LS	1,706-28,750	4-5	11
	Lightly treated LS	142	3	11
	Freshwater LS	4,276-4,509	4	11
	Lime	658	3	11
	FW/SW-LS	3,570	4	11
	Non-dispersed	100,000	6	11
	LTLS	35,420	5	11
	Seawater-K-polymer	2,557	4	11
Penaeus aztecus	Seawater-chrome LS (MAF)	41,500	5	6
juvenile	MDLS (MAF)	16,000	5	6

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS
(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)
(Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
Orchestia traskiana	Seawater-polymer	230,000	6	8
	Pelly gel Chemical XC	80,000	5	8
	KCl-XC-Polymer	14,000	5	8
	Weighted shell polymer	34,000	5	8
	Gel-SX-polymer	420,000--500,000	6	8
	Imnak gel-XC-polymer	560,000	6	8
DECAPODS-CRABS				
Carcinus maenus	LDLS	89,100	5	5
	LDLS (suspended WM)	15,000	5	5
	LDLS (MAF)	100,000	6	5
	MDLS	68,000-100,000	5-6	5
	MDLS (suspended WM)	15,000	5	5
	MDLS (MAF)	100,000	6	5
	HDLS (MAF)	100,000	6	5
Clibanarius vittatus	Seawater-chrome LS (MAF)	28,700	5	6
	MDLS (MAF)	34,500	5	6
	HDLS (MAF)	65,600	5	6
Hemigrapsus nudus	Seawater polymer	530,000	6	8
	Shell Kipnik-KCl polymer	53,000	5	8
	Pelly gell chemical XC	560,000	6	8
	KCl-XC-polymer	78,000	5	8
	Weighted shell polymer	62,000	5	8
	Pelly weighted gel-XC-polymer	560,000	6	8
	Imnak gel-XC-polymer	560,000	6	8
DECAPODS-LOBSTER				
Homarus americanus	LDLS (MAF)	5,000	5	5
Stage V larvae	MDLS	100,000	6	5
	MDLS (MAF)	29,000	5	5
Adult	LDLS	19,000-25,000	5	5
	LDLS (MAF)	100,000	6	5
Larvae	Mobile Bay/Jay fluids	73.8-500 ppm	2-3	10
BIVALVES				
Modiolus modiolus	FCLS/FW	30,000	5	3
		30,000 (14 day LC50)	5	3
Mytilus edilus	Spud mud (MAF)	100,000	6	5
	Seawater LS (MAF)	100,000	6	5
	MDLS (MAF)	100,000	6	5
	MDLS (suspended WM)	15,000	5	5
	HDLS (MAF)	100,000	6	5
	HDLS (suspended WM)	15,000	5	5

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS

(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)

(Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
Macoma balthica	LDLS	100,000	6	5
	LDLS (MAF)	100,000	6	5
	LDLS (suspended WM)	15,000	5	5
	HDLS	100,000	6	5
	HDLS (MAF)	100,000	6	5
	HDLS (FMAF)	100,000	6	5
Placopecten magellanicus	LDLS	49,000	5	5
	MDLS	3,200	4	5
Crassostrea gigas	Spud mud (SPP)	100,000	6	6
	MDLS (SPP)	50,000-53,000	5	6
	HDLS (SPP)	73,000-74,000	5	6
Donax variabilis texasiana	Spud mud (SPP)	100,000	6	6
	Seawater-chrome LS (SPP)	53,700	5	6
	MDLS (SPP)	29,000	5	6
	HDLS (SPP)	56,000	5	6
Mya arenaria	Seawater polymer	320,000	6	8
	Kipnik-KCl polymer	42,000	5	8
	Polly gel chemical XC	560,000	6	8
	KCl-XC-polymer	56,000	5	8
	Weighted shell polymer	10,000	5	8
	Weighted gel XC-polymer	560,000	6	8
	Weighted KCl-XC-polymer	560,000	6	8
	Imnak gel-XC-polymer	560,000	6	8
Mercenaria mercenaria	Seawater LS (LP)	87-3,000	2-4	11
Larvae	Seawater LS (SPP)	117-3,000	3-4	11
	LTLS (LP)	719-3,000	3-4	11
	LTLS (SPP)	122-2,889	3-4	11
	FWLS (LP)	319-330	3	11
	FWLS (SPP)	158-338	3	11
	FW/SW LS (LP)	380	3	11
	FW/SW LS (SPP)	82	2	11
	Lime (LP)	682	3	11
	Lime (SPP)	64	2	11
	Low solids non-dispersed (LP)	3,000	4	11
	Low-solids non-dispersed (SPP)	3,000	4	11
	Potassium polymer (LP)	269	3	11
	Potassium polymer (SPP)	220	3	11
ECHINODERMS				
Strongylocentrotus droebachiensis	LDLS	55,000	5	5
	LDLS (MAF)	100,000	6	5
	MDLS	100,000	6	5
	MDLS (MAF)	100,000	6	5

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS
(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)
(Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
MYSIDS				
Neomysis integer	FCLS/FW	10,000-200,000 (48-h LC50)	5-6	3
		10,000-125,000	5-6	3
Mysis sp.	CMC-Gel	142,000-349,000	6	4
	CMC-Gel-Resinex	58,000-93,000	5	4
	XC-polymer (supernatant)	250,000	6	4
	XC-polymer	50,000-170,000	5-6	4
Mysidopsis almyra	Spud mud (MAF)	100,000	6	6
	Seawater-chrome LS (MAF)	27,000	5	6
	MDLS (MAF)	12,800-13,000	5	6
	HDLS (MAF)	16,000-32,500	5	6
	MDLS (SPP)	32,000	5	12
	MDLS (MAF)	26,800-66,300	5	12
	MDLS (MAF) (static test)	72,100-113,000	5-6	12
	Reference mud(MAF)(static test)	100,000	6	12
Mysidopsis bahia	Seawater LS	429-1,557	3-4	11
	Seawater LS (LP)	150,000	6	11
	Seawater LS (SPP)	15,123-19,825	5	11
	Seawater LS (SP)	50,000	5	11
	LTLS	14-1,958	2-4	11
	LTLS (LP)	150,000	6	11
	LTLS (SPP)	1,641-50,000	3-5	11
	LTLS (SP)	1,246-2,437	3	11
	FWLS	301-1,500	3-4	11
	FWLS (LP)	97,238-121,476	5-6	11
	FWLS (SPP)	14,068-29,265	5	11
	Lime	87-98	2	11
	Lime (SPP)	650-791	3	11
	Lime (SP)	8,213-1,369,393	4-6	11
	FW/SW-LS	115-379	3	11
	FW/SW-LS (LP)	150,000	6	11
	FW/SW-LS (SPP)	11,380-38,362	5	11
	FW/SW-LS (SF)	50,000	5	11
	Low-solids non-dispersed	1,500	4	11
	Low-solids non-dispersed (LP)	150,000	6	11
	Low-solids non-dispersed (SPP)	50,000	5	11
	Low-solids non-dispersed (SP)	50,000	5	11
	Potassium polymer	1,500	4	11
	Potassium polymer (LP)	150,000	6	11
	Potassium polymer (SPP)	26,025-28,070	5	11
POLYCHAETES				
Melaenis loveni	CMC-Resinex-Tannathin	600,000	6	4
	CMC-Resinex-Tannathin-Gel	700,000	6	4

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS
(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)
(Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
Nereis virens	Spud mud (MAF)	100,000	6	5
	Seawater-LS (MAF)	100,000	6	5
	LDLS	100,000	6	5
	LDLS (MAF)	100,000	6	5
	MDLS	100,000	6	5
	MDLS (MAF)	100,000	6	5
	HDLS	100,000	6	5
	HDLS (MAF)	100,000	6	5
Ophryotrocha labronica	Spud mud (MAF)	100,000	6	6
	Seawater-chrome LS (MAF)	100,000	6	6
	MDLS (MAF)	60,000	5	6
	HDLS (MAF)	100,000	5	6
Neveis vexillosa	Seawater polymer	220,000	6	8
	Kipnik-KCl polymer	37,000	5	8
	Gel chemical XC	560,000	6	8
	KCl-XC-polymer	41,000	5	8
	Weighted shell polymer	23,000	5	8
	Weighted gel XC-polymer	320,000-560,000	6	8
	Imnak gel-XC-polymer	200,000	6	8
TELEOST FISH				
Menidia menidia	Imco LDLS/SW	56,500-175,000	5-6	1
	Imco Lime	43,000-53,000	5	1
	Imco non-dispersed	345,000-385,000	6	1
	Saltwater gel	100,000	6	2
	LSLS-SW/FW	48,500	5	2
	FCLS	100,000	6	2
Oncorhynchus gorbuscha	FCLS/FW	3,000-29,000	4-5	3
Leptocuttus armatus	FCLS/FW	100,000-200,000	6	3
Myoxocephalus quadricornis	CMC-Gel	120,000	6	4
	CMC-Gel-Resinex	50,000-70,000	5	4
	XC-Polymer	50,000-215,000	5-6	4
	XC-Polymer (supernatant)	250,000	6	4
	Lignosulfonate	350,000	6	4
Coregonus nasus	CMC-Gel	200,000	6	4
	XC-Polymer	57,000-370,000	5-6	4
	XC-Polymer (supernatant)	100,000-250,000	6	4
	Lignosulfonate	0-100,000	6	4
Elegonus naraga	CMC-Gel	170,000-300,000	6	4
Boreogodus saida	XC-Polymer	250,000	6	4
	Lignosulfonate	200,000-250,000	6	4
Coregonus autumnalis	Lignosulfonate	85,000-1,000,000	6	4

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS
(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)
(Continued)

Test organism	Fluid description[a]	Criterion value (ppm)	Toxicity rating[b]	Reference[c]
Fundulus heteroclitus	Spud mud (MAF)	100,000	6	5
	Seawater-LS (MAF)	100,000	6	5
	MDLS (suspended whole mud)	15,000	5	5
	MDLS (MAF)	100,000	6	5
	HDLS (suspended whole mud)	15,000	6	5
	HDLS (MAF)	100,000	6	5
Salmo gairdneri (juvenile)	Kipnik-KCl polymer	24,000-42,000	5	8
	Seawater polymer	130,000	6	8
	KCl-XC polymer	34,000	5	8
	Weighted shell polymer	16,000	5	8
	Pelly gel chemical-XC	42,000	5	8
	Weighted gel XC-polymer	18,000-48,000	5	8
	Imnak-Gel XC-polymer	42,000	5	8
Oncorhynchus kisutch (juvenile)	Kipnik-KCl polymer	29,000	5	8
	Seawater polymer	130,000	5	8
	KCl-XC polymer	20,000-23,000	5	8
	Weighted shell polymer	4,000-15,000	4-5	8
	Pelly Gel chemical-XC	28,000-130,000	5-6	8
	Weighted gel XC-polymer	24,000-190,000	5-6	8
	Imnak-Gel XC-polymer	23,000-30,000	5	8
O. keta (juvenile)	Kipnik-KCl polymer	24,000	5	8
O. gorbuscha (juvenile)	Kipnik-KCl polymer	41,000	5	8
	DRILLING FLUID COMPONENTS			
Skeletonema costatum	Barite	385-1,650	3-4	2
	Aquagel	9,600	4	3
Arcartia tonsa	Barite	590	3	2
	Aquagel	22,000	5	2
Pandalus hypsinotus	Barite	100,000	6	3
	Aquagel	100,000	6	3
Molliensias latipinna	Barite	100,000	6	13
	Calcite	100,000	6	13
	Siderite	100,000	6	13
	Chrome lignosulfonate	7,800-12,200	4-5	14
	Quebracho	135-158	3	14
	Lignite	15,500-24,500	5	14
	Sodium acid pyrophosphate	1,200-7,100	4	14
Penaeus setiferus	Hemlock bark extract	265	3	15
	Polyacrylate	3,500	4	15
	$CaCO_3$ workover additive	1,925	4	15
	Chrome-treated lignosulfonate	465	3	15
	Lead-treated lignosulfonate	2,100	4	15

TABLE 4-3 ACUTE LETHAL TOXICITIES OF USED DRILLING FLUIDS AND DRILLING FLUID COMPONENTS TO MARINE ORGANISMS
(96-hour LC_{50} unless otherwise noted; adapted from Petrazzuolo, 1981)
(Continued)

[a] Drilling fluids abbreviations (fluid fractions in parenthesis):

Fractions:
WM = Whole Mud
MAF = Mud aqueous fraction
FMAF = Filtered mud aqueous fraction
SPP = Suspended particulate phase
SP = Solid phase
LP = Liquid phase

Descriptions:
/SW = Saltwater dispersant
/FW = Freshwater dispersant
LS = Lignosulfonate
LDLS = Low density lignosulfonate
MDLS = Medium density lignosulfonate
HDLS = High density lignosulfonate
LTLS = Lightly treated lignosulfonate
FCLS = Ferrochrome lignosulfonate

[b] Toxicity ratings as per Hocutt & Stauffer, 1980.
1. Very toxic (1 ppm)
2. Toxic (1-100 ppm)
3. Moderately toxic (100-1,000 ppm)
4. Slightly toxic (1,000-10,000 ppm)
5. Practically non-toxic (10,000-100,000 ppm)
6. Non-toxic (100,000 ppm)

[c] References:
1. Imco, 1977.
2. Shell Oil Co., 1976 as cited in Petrazzuolo, 1981.
3. Atlantic Richfield, 1978, as cited in Petrazzuolo, 1981.
4. Tornberg et al., 1980.
5. Gerber et al., 1980.
6. Neff et al., 1980.
7. Conklin et al., 1980.
8. Environmental Protection Service, 1975, as cited in Petrazzuolo, 1981.
9. Conklin et al., 1983.
10. Capuzzo and Derby, 1982.
11. Duke et al., 1983 (or Rao, 1983).
12. Carr et al., 1980.
13. Grantham and Sloan, 1975, as in Petrazzuolo, 1981.
14. Hollingsworth and Lockhart, 1975.
15. Chesser and McKenzie, 1975.

with nine parts seawater, so an LC_{50} value derived from 100 percent MAF is actually the supernatant from a 10 percent drilling fluid mixture and is therefore expressed as 100,000 ppm (10 percent whole fluid equivalent).

The calanoid copepod Acartia tonsa is one species that exhibited sensitivity to drilling fluid and displayed a 96-hour LC_{50} of 100 ppm for both a used seawater gel and a ferrochrome lignosulfonate freshwater drilling fluid (Shell Oil Company, 1976, as in Petrazzuolo, 1981). A replicate test of the ferrochrome lignosulfonate mud showed a 96-hour LC_{50} of 230 ppm, confirming the earlier results. IMCO Services (1977, as in Petrazzuolo, 1981) conducted a study exposing Acartia tonsa to four light-density lignosulfonate fluids, a lime fluid, and a nondispersed fluid (primarily barite and bentonite) with 96-hour LC_{50} results of 5,300 to 9,300 ppm for the first five fluids, and 66,500 ppm for the nondispersed fluid.

Pink salmon fry (Onchorhyncus gorbuscha) and several species of crustacea including a shrimp (Pandalus hypsinotus), a mysid (Neomysis integer), an amphipod (Eogammarus confervicolus), and an isopod (Gnorimosphaeroma oregonensis) were exposed to used high-density lignosulfonate drilling fluid from Lower Cook Inlet, Alaska. Pink salmon fry were the most sensitive, with 96-hour LC_{50}'s ranging from 3,000 ppm for the SSP to 24,000 ppm for LSP. The range for crustaceans was from 32,000 to more than 200,000 ppm (Houghton et al., 1981).

In another experiment, stage 1 larvae of king crab, tanner crab, dungeness crab, coonstripe shrimp, dock shrimp, and kelp shrimp were exposed to LSP and FMAF of new and used drilling fluids. The 144-hr LC_{50}'s for the most toxic drilling fluid ranged from 500 to 9,400 ppm for the LSP and 6,000 to 6,700 ppm for the FMAF, indicating that the LSP fraction was more toxic than the FMAF. The particulate fraction was estimated to account for 80 percent of the observed toxicity, and the water-soluble fraction the remaining 20 percent (Carls and Rice, 1981).

Tornberg et al. (1980) found used drilling fluids to be of low toxicity to arctic marine organisms (Table 4-4). The 96-hour LC_{50}'s ranged from 40,000 to 700,000 ppm.

Seven arctic polymer drilling fluids were used for toxicity testing of salmon (Houghton et al., 1981). Five of the seven fluids displayed a 96-hour LC_{50} of less than 40,000 ppm for the SSP fraction; the most toxic fluid had a 96-hour LC_{50} of 15,000 ppm, and the least toxic fluid a 96-hour LC_{50} of 190,000 ppm. Clam worms (polychaetes), soft-shelled clams, purple shore crabs, and sand fleas had approximately the same sensitivity to the fluids as did the salmon. These invertebrate 96-hour LC_{50}'s ranged from 10,000 to more than 560,000 ppm.

In another cold-water test, Gerber et al. (1980) exposed organisms to a seawater lignosulfonate mud and found 96-hour LC_{50}'s ranging from 320,000 to greater than 1,000,000 ppm MAF (corresponding to 32,000 to greater than 100,000 ppm whole drilling fluid). When exposed to the LSP of a low-, medium-, and high-density lignosulfonate drilling fluid and spud mud (Table 4-5), adult sea scallops and adult lobsters were the most sensitive of the cold-water organisms tested, with 96-hour LC_{50}'s of 3,200 ppm and 290,000 ppm, respectively.

TABLE 4-4 TOXICITY OF LAYERED SOLID PHASE (LSP) OF USED DRILLING FLUIDS TO ARCTIC MARINE ORGANISMS
(Tornberg et al., 1980)

Organism	96-hr LC50 (ppm)
Isopods, snails, polychaetes	400,000 to 700,000
Mysids	60,000 to 220,000
Amphipods	220,000 to 380,000
Broad whitefish	60,000 to 370,000
Four horn sculpin	40,000 to 350,000
Arctic cod	200,000 to 250,000
Saffron cod	170,000 to 300,000

TABLE 4-5 96-HOUR LC_{50}'s FOR SEVERAL SPECIES EXPOSED TO FOUR DRILLING FLUIDS

Species	Whole mud LC_{50}'s (ppm)			
	HDLS[a]	MDLS[a]	LDLS[a]	SM[a]
Crustaceans				
Crangon septemspinosa	92,000	82,000	71,000	
Gammarus locusta	28,000	74,000		>100,000
G. locusta	88,000	90,000		>100,000
Pandalus borealis (Stage I)				
Carcinus maenas	>100,000	68,000	89,000	
Homarus americanus[b]		29,000	19,000	
Bivalve Mollusks				
Mytilus edulis				
Macoma balthica	>100,000		>100,000	
Placopecten magellanicus		<3,200[c]	49,000	
Gastropod Mollusks				
Littorina littorea	>100,000	<100,000		
Thais lapillis			83,000	
Polychaete Worms				
Nereis virens	>100,000	>100,000	>100,000	
Echinoderms				
Strongylocentrotus sp.		>100,000	55,000	
Fish				
Fundulus heteroclitus				>100,000

Gerber et al., 1980

[a] HDLS = High density lignosulfonate drilling mud.
MDLS = Medium density lignosulfonate drilling mud.
LDLS = Light density lignosulfonate drilling mud.
SM = Spud mud.

[b] Mud Aqueous Fraction (MAF) changed daily.

[c] This value is in ml of mud/liter of seawater and represents a 1mm thick layer spread over natural mud in the aquarium.

Neff et al. (1981) exposed several marine species to used chrome lignosulfonate drilling fluids and attributed the solid and liquid phase lethality to different mechanisms. They hypothesized that the lethality of the liquid fraction (MAF) stemmed from toxic effects of the water soluble compounds, especially volatile organic compounds. The solid fraction lethality was thought to be caused by both chemical toxicity of soluble mud components, gill clogging from the suspended solids phase, and smothering for the layered solid phase.

Petrazzuolo (1981) used a semi-quantitative procedure to rank organisms in terms of sensitivity to drilling fluids, based on laboratory tests. The results ranked groups of organisms as follows, in order of decreasing sensitivity: copepods and other plankton; shrimp; lobster; mysids and finfish; bivalves; crab; amphipods; echinoderms; gastropods and annelids; and isopods. This ranking is admittedly biased because it is limited by the actual bioassay test results which have been published, and not based on theoretical considerations. For example, if more tests, more toxic drilling fluids, and more sensitive life stages have been tested on certain types of organisms, they would appear to be more sensitive in the rankings. These shortcomings notwithstanding, the ranking is a reasonable general indicator of the relative sensitivity of organisms to drilling fluid.

Toxicity tests also highlight the toxicity variations which occur during a given organism's life cycle. Larval stage organisms are more sensitive than adult stages, and animals are more sensitive while molting than during intermolt stages. These variations affect the potential for impact associated with offshore operations. Drilling fluids discharged into an area occupied by an adult community will presumably cause less impact than if the area were occupied by juvenile communities or serves as a breeding ground. Many organisms, including several commercially important species, have breeding or nursery grounds in estuaries or salt marshes.

As drilling progresses on a given hole, increasing temperature and pressures place increasing demands on the properties of the drilling mud. This often necessitates the use of greater quantities of both basic and specialized mud components, which will presumably increase mud toxicity. Thus, while every well is different, it is reasonable to expect a general trend of increasing mud toxicity with increased well depth. However, the addition of specialty additives is dictated by well-specific needs which may be more severe at one geologic stratum than another, and thus, mud taken from that stage of drilling may contain more additives and be more toxic than deeper stages.

Some drilling fluids have exhibited toxicities much higher than average. One drilling fluid from Mobile Bay, Alabama, exhibited a 96-hour LC_{50} of approximately 100 ppm. Other experiments by Rubenstein and Rigby (1980) found mortality to lugworms, some toxicity to mysids, and inhibition of oyster growth at concentrations less than 100 ppm, in 10-100 day flow-through bioassay experiments. Analyses of these fluids indicate hydrocarbon distributions characteristic of diesel oil, which contribute significantly to the toxicity but are probably not its sole source. However, the Mobile Bay fluid was subject to Alabama's restrictions prohibiting oil and gas activity discharges into territorial waters, and industry has argued that the fluid was formulated with the intention that it would not be discharged.

Several recent studies have examined the relationship between diesel oil content and the toxicity of drilling fluids. An EPA project team has recently completed bioassays on samples of eleven drilling fluids collected from operating rigs in the Gulf of Mexico. The rigs were chosen at random and represent different geographical areas and well depths.

The preliminary results of the many tests conducted are presented in Table 4-6. Bioassays with Mysidopsis bahia revealed that whole muds were more toxic than the various fractions, and that the suspended solid phase was consistently more toxic than the liquid phase. Whole mud 96-hour LC_{50}'s ranged from 14 to 1,958 ppm. Two of the mud samples had mean LC_{50}'s in the range from 10 to 99 ppm, and four in the range from 100 to 999 ppm. The 96-hour LC_{50} values for the suspended particulate phase ranged from 650 to > 50,000 ppm.

Toxicity tests with larvae of the grass shrimp (Palaemonetes pugio) (Table 4-7) indicated that they are not as sensitive to whole muds as the mysids. Average 96-hour LC_{50} values for whole muds ranged from 142 to 100,000 ppm. Mercenaria mercenaria one-hour larvae showed a lack of development (48-hour EC_{50}) at relatively low concentrations of the liquid and suspended solids phases of the muds (Table 4-8). Concentrations as low as 87 and 64 ppm (respectively) halted larval development. Similarly, embryogenesis of Fundulus and echinoderms was affected by drilling fluid exposure. "Safe" levels (defined as a concentration of 10 percent of that having an adverse effect on the most sensitive assay system) ranged from one to 100 ppm. A study of sublethal effects of drilling mud on corals (Acropora

TABLE 4-6 TOXICITY OF USED DRILLING FLUIDS TO MYSIDS (*MYSIDOPSIS BAHIA*)

Duke and Parrish (1980)

		96-Hour LC$_{50}$^{1} (ppm; µl/l)			
EPA Mud Code	Mud Type	Whole Mud	Liquid Phase	Suspended Particulate Phase^{2}	Solid Phase
MIB	Seawater lignosulfonate	>1,500^{3}	NT^{4}	NT	NT
AN31	Seawater lignosulfonate	1,008(541-1,557)	>150,000	NT	NT
SV76	Seawater lignosulfonate	733 (429-888)	>150,000	17,633 (15,123-19,835)	>50,000
P1	Lightly treated lignosulfonate	26(14-39)	>150,000	1,936 (1,641-2,284)	1,456 (1,246-2,437)
P2	Freshwater lignosulfonate	459 (301-732)	116,419 (111,572-121,476)	18,830 (14,068-22,522)	NT
P3	Lime	92 (87-98)		726 (650-791)	11,304 (8,213-1,369,393)
P4	Freshwater lignosulfonate	>1,500	97,238	27,233 (24,791-29,265)	NT
P5	Freshwater/seawater lignosulfonate	263(115-379)	>150,000	24,770 (11,380-38,362)	>50,000
P6	Low solids nondispersed	>1,500	>150,000	>50,000	>50,000
P7	Lightly treated lignosulfonate	728(470-1,958)	>150,000	>50,000	NT
P8	Seawater/potassium/polymer	>1,500	>150,000	27,137 (26,025-28,070)	NT

Adapted from Duke and Parrish, 1984.

[1] Results of probit analyses; 95% confidence limits are in parentheses.

[2] The suspended particulate phase (SPP) was prepared by mixing 1 part drilling fluid with 4 parts seawater. Therefore, these values should be multiplied by 0.20 in order to relate the 1:4 dilution tested to the SPP of the whole drilling fluid.

[3] The toxicity concentrations for the "greater than" values (>1,500, >150,000, >50,000) were arbitrarily selected for these specific tests.

[4] Not tested.

TABLE 4-7 DRILLING FLUID TOXICITY TO GRASS SHRIMP (*PALAEMONETES INTERMEDIUS*) LARVAE[1]

Mud	Type	96-h LC_{50} (95% CL)
MIB	Seawater Lignosulfonate	28,750 ppm (26,332-31,274)
AN31	Seawater Lignosulfonate	2,390 ppm (1,896-2,862)
SV76	Seawater Lignosulfonate	1,706 ppm (1,519-1,922)
P1	Lightly Treated Lignosulfonate	142 ppm (133-153)
P2	Freshwater Lignosulfonate	4,276 ppm (2,916-6,085)
P3	Lime	658 ppm (588-742)
P4	Freshwater Lignosulfonate	4,509 ppm (4,032-5,022)
P5	Freshwater/Seawater Lignosulfonate	3,570 ppm (3,272-3,854)
P6	Low Solids Nondispersed	100,000 ppm ---
P7	Lightly Treated Lignosulfonate	35,420 ppm (32,564-38,877)
P8	Seawater/Potassium/Polymer	2,577 ppm (2,231-2,794)
NBS Reference		17,917 ppm (15,816-20,322)

[1] All tests conducted at 20 ppt salinity and 20±2°C with Day-1 larvae (Conklin and Rao, in press).

Adapted from Duke and Parrish (1984).

TABLE 4-8

RESULTS OF CONTINUOUS EXPOSURE (48 h) of 1-h OLD FERTILIZED EGGS OF HARD CLAMS (*Mercenaria mercenaria*) TO LIQUID AND SUSPENDED PARTICULATE PHASES OF VARIOUS DRILLING FLUIDS. THE PERCENTAGE OF EACH TEST CONTROL (n = 625±125 eggs) THAT DEVELOPED INTO NORMAL STRAIGHT-HINGE OR "D" STAGE LARVAE AND THE EC_{50} IS GIVEN[1]

Drilling Fluid	Liquid Phase EC_{50} (ul/l)[2]	Control % "D" Stage	Suspended Particulate EC_{50} (ul/l)[2]	Control % "D" Stage
AN31	2,427(2,390-2,463)	88	1,771 (1,710-1,831)	93
MIB	>3,000	95	>3,000	95
SV76	85(81-88)	88	117(115-119)	93
P1	712(690-734)	97	122(89-151)	99
P2	318(308-328)	97	156(149-162)	99
P3	683(665-702)	98	64(32-96)	99
P4	334(324-345)	98	347 (330-364)	99
P5	385(371-399)	98	382(370-395)	99
P6	>3,000	97	>3,000	93
P7	>3,000	97	2,799(2,667-2,899)	93
P8	269(257-280)	93	212(200-223)	93

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[1] From NEA (1984) in Duke and Parrish (1984).

[2] EC_{50} and 95% confidence limits.

cervicornis) indicated a decrease in the calcification rate and changes in amino acids at concentrations of 25 ppm.

All of the muds tested in this study were found to contain some No. 2 fuel (diesel) oil. Surrogate "Diesel" oil content ranged from 0.10 to 9.43 mg/g in the whole mud. Spearman Rank Order Correlation of the relationship between toxicity and fuel oil content showed a significant correlation between these factors in all tests. In all cases, the drilling fluids with higher diesel oil contents were more toxic to the organisms tested. A higher correlation was found with "diesel" (equivalent to API #2 fuel oil) content than with either aromatic or aliphatic content. Toxicity also correlated better with organics in the suspended particulate phase than with organics in the whole mud, except for aromatics.

	Chemical Content		
Toxicity	Aromatic	Aliphatic	"Diesel"
Whole Mud	-0.79	-0.77	-0.81
Suspended Particulate Phase	-0.77	-0.89	-0.96

Since all of the muds contained some diesel oil, and the oil is clearly a factor in toxicity, then addition of diesel oil is a likely contributor to the increased toxicity of used versus unused drilling fluids.

Duke and Parrish (1984) found a significant negative correlation (-0.976) between 96-hour LC_{50} and mineral oil content of two generic muds. The mineral oil was added in concentrations of 1 percent, 5 percent, and 10 percent to generic muds #2 and #8. When 1 percent mineral oil was added, the 96-hour LC_{50} decreased from 51.6 percent to 13.4 percent for generic mud #2 and from 29.3 percent to 7.1 percent for generic mud #8. With 10 percent mineral oil, the LC_{50} dropped to 0.49 percent for mud #2 and 0.76 percent for mud #8.

Conklin et al. (1983) also found a significant relationship between the toxicity of drilling fluids and diesel oil content. Their study was designed to assess the roles of chromium and petroleum hydrocarbons in the total toxicity of whole mud samples from Mobile Bay to adult grass shrimp (Palaemonetes pugio). The range of 96-hour LC_{50} values was from 360 to 14,560 ppm. The correlation between chromium concentration of the mud and the LC_{50} value was not significant; however, the correlation between diesel oil concentration and the LC_{50} value was significant. As the concentration of diesel oil in the muds increased, there was a general increase in the toxicity values. Similar toxicity tests using juvenile sheepshead minnows (Cyprinodon variegatus) showed higher LC_{50} levels but no significant correlation between either chromium or diesel oil content and toxicity.

Capuzzo and Derby (1982) examined the effects of drilling fluids on the developmental stages of the American lobster. They tested a land-based "Jay" fluid and two fluids from Mobile Bay. The lowest 96-hour LC_{50} observed was less than 100 ppm. Again, the toxicity of a particular fluid was apparently related to the diesel oil content. The fluid exhibiting the lowest toxicity contained no diesel oil, while the two fluids with the highest toxicity contained two and four percent diesel oil, respectively.

Breteler et al. (1984) have examined the acute toxicity of the suspended particulate and solid phases of a laboratory formulated generic mud to which various amounts of mineral oil and diesel fuel had been added. Animals tested included Mya arenaria, the sandworm Nereis virens, and the grass shrimp Palaemonetes pugio. The results generally agree with those of previous studies. Mud to which diesel fuel had been added was the most toxic, and the base mud was the least toxic. Mud to which mineral oil had been added showed a toxicity between these two extremes, and was approximately an order of magnitude less toxic than diesel oil.

Addition of 0.5 percent to 5 percent mineral oil to the base mud increased the toxicity of the suspended particulate phase proportionally, resulting in a "moderate" toxicity at the 5 percent additive level. The suspended particulate phase of mud containing 5 percent low or high sulfur diesel fuel additive resulted in 50 percent mortality among mysid shrimp at 45 and 28 ppm mud added, respectively. Toxicity was directly proportional to the concentration of added diesel fuel in the mud. It is noted that substantial fractions of the toxic aromatics in their mud were probably lost during handling and preparation of the mud for testing, and, thus the results likely underestimate the acute toxicity somewhat.

No mortality was observed in the marine animals following exposure to the solid phase of the mud containing 0.5 to 5 percent mineral oil. However, the solid phase of muds containing diesel fuel were toxic, with the high sulfur diesel being more toxic than the low sulfur diesel.

There are still some unresolved issues with regard to toxicity. One is the actual cause(s) of toxicity; another is consistency (a) for the same muds and (b) between laboratories. In 1981 EPA required a series of bioassays be performed on generic muds that were to be used in Regions I and II. The tests were duplicated at two laboratories using sample splits of each mud type. Results (Table 4-9) were, in some cases, comparable and at other times different by an order of magnitude. There were general guidelines as to how samples were handled and tests performed, but much of the observed differences may be due to differences in the protocols used by different laboratories. EPA has since published a more detailed protocol for the handling and testing of samples (Petrazzuolo, 1984).

A second source of discrepancy is in the types of drilling muds. Generic muds are defined by a range for each component and separate batches of a generic mud given the same name may show differing toxicity. Tests on two sets of No. 2 and No. 8 muds provided to EPA and ERCO produced the following LC_{50}'s whole mud equivalents (Duke et al., 1984, ERCO 1984).

	ERCO	EPA
#2	7,100 ppm	62,000 ppm
#8	16,000 ppm	30,000 ppm

Unfortunately, chemical analyses were not reported for the muds used in the ERCO tests and so the possible cause of toxicity difference cannot be explained. EPA did, however, get good correspondence when comparative tests were performed on muds from the same batch at the Gulf Breeze and Narragansett laboratories.

TABLE 4-9
SUMMARY OF BIOASSAYS(1)

Mud No.	Mud Type(4)	Density (l/gal)	Laboratory	Toxicity Data(3) Mysid Shrimp (LC$_{50}$-ppm) 96 hr. Liquid	Toxicity Data(3) Mysid Shrimp (LC$_{50}$-ppm) 96 hr. Suspended Particulate	Hard Clams(2) Solid
1	Potassium/Polymer/ Seawater	9.3	ERCO	66,000	25,000	90% Survival
			NA(5)	58,000	70,900	88% Survival
2	Lignosulfonate	12.1	ERCO	283,000	53,200	83.0% Survival
			NA(5)	880,000	870,000	70% Survival
3	Lime	10.4	ERCO	393,000	66,000	100% Survival
			NA	55% Survival at 1,000,000 ppm	860,000	94% Survival
4	Nondispersed	9.2	ERCO	91.7% Survival at 1,000,000 pm	86.7% Survival at 1,000,000 ppm	100% Survival
			NA	96.7% Survival at 1,000,000 ppm	88.3% Survival at 1,000,000 ppm	100% Survival
5	Seawater Spud Mud	8.2	ERCO	98.3% Survival	96.7% Survival at 1,000,000 ppm	100% Survival
			NA	80% Survival at 1,000,000 ppm	88.3% Survival at 1,000,000 ppm	100% Survival
6	Seawater/Freshwater Gel	9.3	ERCO	88.4% Survival at 1,000,000 ppm	224,000	100% Survival
			NA	517,000	51.7% Survival at 1,000,000 ppm	100% Survival
7	Lightly Treated Lignosulfonate	9.6	ERCO	51.7% Survival at 1,000,000 ppm	55% Survival at 1,000,000 ppm	97% Survival
			NA	70% Survival at 1,000,000 ppm	86% Survival at 1,000,000	100% Survival
8	Lignosulfonate Freshwater	9.3	ERCO	95% Survival at 1,000,000 ppm	506,000	99% Survival
			NA	90% Survival at 1,000,000 ppm	75% Survival at 1,000,000 ppm	99% Survival

(1) Procedures described in Annex I of protocols developed by EPA Region II and OOC (1980).
(2) 10-day exposure.
(3) Complete reports filed with EPA Regions I and II.
(4) Composition, properties and metals analysis attached.
(5) Normandeau Associates.
Adapted from Michaels, 1984.

While we know that certain additives, such as diesel oil and mineral oil, increase the toxicity of drilling muds (Table 4-10), there is no simple explanation and several factors may be involved. In recent tests by ERCO and EPA, low dissolved oxygen levels (DO) were reported. This occurred in spite of the fact that samples were aerated to bring DO up to saturation before animals were added and aeration continued through the experiment. Drilling muds do exhibit significant oxygen demand (see Section 2) and the possibility of this being a factor in toxicity tests has not been fully evaluated.

To further investigate this factor, LC_{50} data for eight generic muds were correlated with a variety of oxygen related parameters. These included 5-day biological oxygen demand (BOD_5), 20-day ultimate oxygen demand (UOD_{20}), chemical oxygen demand (COD), and total organic carbon (TOC). The data used were those reported by Duke and Parrish (1984) for LC_{50}'s. Oxygen demand and total organic carbon data were taken from the CENTEC (1984) analysis of the same muds. Spearman Rank correlations are listed in Table 4-11. Correlations between toxicity and both BOD_5 and UOD_{20} were very high (0.87-0.97) with the highest correlation for BOD_5 (CENTEC activated seed in artificial sea water), which was the best indicator of BOD tested by CENTEC (1984). There was not quite as good a correlation between toxicity and either TOC or COD (0.67).

As indicated earlier, the oxygen levels in test chambers were enhanced by aeration, and thus the strong correlation between toxicity and oxygen demand is all the more surprising.

TABLE 4-10

TOXICITY OF API #2 FUEL OIL, MINERAL OIL, AND OIL-CONTAMINATED DRILLING FLUIDS TO GRASS SHRIMP (PALAEMONETES INTERMEDIUS) LARVAE[1]

Materials Tested	Oil Added (g/1)	Total oil Content (g/1)	96-h LC_{50} & 95% CL[2] (ppm; ul/1)
API #2 fuel oil[3]	—	—	1.4 (1.3-1.6)
Mineral Oil[4]	—	—	11.1 (9.8-12.5)
P7 mud	None	0.68	35,400 (32,564-38,877)
P7 mud + API #2 fuel	17.52	18.20	177 (165-190)
P7 mud + API #2 fuel oil (hot-rolled)	17.52	18.20	184 (108-218)
P7 mud + mineral oil	17.52	18.20	538 (446-638)
P7 mud + mineral oil (hot-rolled)	17.52	18.20	631 (580-674)
NBS reference drilling mud	None	0	17,900 (15,816-20,332)
NBS mud + API #2 fuel oil	18.20	18.20	114 (82-132)
NBS mud + API #2 fuel oil (hot-rolled)	18.20	18.20	116 (89-133)
NBS mud + mineral oil	18.20	18.20	778 (713-845)
NBS mud + mineral oil (hot-rolled)	18.20	18.20	715 (638-788)
P1 drilling mud	None	18.20	142 (133-153)

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[1] From Conklin and Rao (In press).

[2] 95% confidence limits computed by using a "t" value of 1.96.

[3] Properties: Specific gravity at 20°C, 0.86; Pour point -23°C; Visocity, Saybolt, 38°C, 36; Saturates, wt% 62; Aromatics, wt% 38; Sulfur, wt%, 0.32.

[4] Properties: Specific gravity at 15.5°C, 0.84-0.87; Flash point, 120-125°C; Pour point, -12 to -15°C; Aniline point, 76-78°C; Visocity, CST 40°C, 4.1 to 4.3; Color Saybolt, +28; Aromatics, wt%, 16-20; Sulfur, 400-600 ppm.

Adapted from Duke and Parrish, 1984.

TABLE 4-11

SPEARMAN RANK
CORRELATION BETWEEN LC_{50}'s AND THE FOLLOWING PARAMETERS

Parameter	Spearman Rank Using Max. Conc.	Spearman Rank Adjusted for Ties Using Max. Conc.	Spearman Rank Adjusted for Ties Using Ave. Conc.
BOD_5[1]	0.96	0.93	0.97
BOD_5[2]	0.86	0.83	
BOD_5[3]	0.87	0.85	
TOC	0.67	0.64	0.69
COD	0.67	0.64	
UOD_{20}[4]	0.95	0.93	
UOD_{20}[5]	0.91	0.88	
UOD_{20}[6]	0.93	0.90	

1. Artificial seawater with CENTEC activated seed (BOD_5).
2. Regular dilution water with regular seed (BOD_5).
3. Artificial seawater matrix with polyseed (BOD_5).
4. SOW Matrix (synthetic seawater) using CENTEC Activated Seed.
5. Regular dilution water using regular sewage seed (UOD_{20}).
6. SOW matrix using polyseed (UOD_{20}).

BOD_5 may in fact reflect some other property of the muds, such as clay or lignite content, which is then responsible for toxicity in the tests.

It is quite clear that much more information is needed to clarify the issue of the causative factors for the acute toxicity of muds. It is quite probable that some of the mortality seen in these tests is due to physical aspects such as burial or gill-clogging. This may explain the wide range of toxicity shown by the eight generic muds (2,700 ppm - 65,000 ppm: Table 4-12).

4.3.2 Chronic Toxicity of Drilling Fluids

Petrazzuolo (1981, 1983a) and Houghton et al. (1981) reviewed a number of toxicity tests designed to measure chronic toxicity of drilling fluids. Several of these studies had to be discounted because of flawed methods. Only data from those studies found accurate and reasonable by Petrazzuolo and Houghton are included below.

4.3.2.1 Stress Tests on Corals

There has been considerable investigation regarding the effects of whole drilling fluids on corals, due to their sensitivity, ecological interest, and presence in the Texas Flower Garden Banks area, which is currently under exploration (see Section 5). Respiration, excretion, mucous production, degree of polyp expansion, and clearing rates for materials deposited on the surface are all useful parameters for indicating stress.

TABLE 4-12 RESULTS OF ACUTE TOXICITY TESTS WITH EIGHT LABORATORY-PREPARED GENERIC DRILLING FLUIDS AND MYSIDS (*MYSIDOPSIS BAHIA*)

Test Location	Drilling Fluid	Definitive Test[1] (96-h LC_{50} & 95% CL)	Positive Control[1] (96-h LC_{50} & 95% CL)	Definitive Test[2] (96-h LC_{50} & 95% CL)
Gulf Breeze	#1	2.7% SPP[3] (2.5–2.9)	5.8 ppm[4] (4.3–7.6)	3.3% SPP (3.0–3.5)
	#2	51.6% SPP (47.2–56.5)	7.5 ppm (6.9–8.1)	62.1% SPP (58.3–65.4)
	#3	16.3% SPP (12.4–20.2)	7.3 ppm (6.6–8.1)	20.3% SPP (15.8–24.3)
	#4	12% mortality in 100% SPP	3.4 ppm (2.8–4.1)	—
	#5	12% mortality in 100% SPP	Same as for #1	—
	#6	20% mortality in 100% SPP	6.0 ppm (5.4–6.6)	—
	#7	65.4% SPP (54.4–80.4)	Same as for #6	68.2% SPP (55.0–87.4)
	#8	29.3% SPP (27.2–31.5)	Same as for #3	30.0% SPP (27.7–32.3)
Narragansett	#1	2.8% (2.5–3.0)	6.2 ppm (4.4–11)	—
	#5	No mortality in 100% SPP	3.3 ppm (2.6–3.8)	—

Adapted from Duke and Parrish, 1984.

[1] Calculations by moving average; no correction for control mortality unless stated.

[2] Calculations by SAS® probit; correction for all control mortality. Analyses performed R. Clifton Bailey, U.S. EPA, Program Integration and Evaluation Staff (WH-586), Office of Water Regulations and Standards, Washington, D.C. 20460.

[3] The suspended particulate phase (SPP) was prepared by mixing 1 part drilling fluid with 9 parts seawater. Therefore, these values should be multiplied by 0.1 in order to relate the 1:9 dilution tested to the SPP of the whole drilling fluid.

[4] Corrected for 13% control mortality.

Laboratory experiments using the corals Montastrea and Diplora showed essentially unchanged clearing rates after applications of calcium carbonate, barite, and bentonite. However, exposure to a used drilling fluid significantly decreased clearing rates, although dose quantification was not possible (Thompson and Bright, 1977, as in Petrazzuolo, 1981). When seven coral species were studied using in situ exposures to used drilling fluid (Thompson and Bright, 1980), Montastrea and Agaricia displayed no mortality after a 96-hour exposure to 316 ppm concentrations, but 100 percent mortality at the 1,000 ppm level. Stress reactions were displayed by six species at the 316 ppm exposure level, including partial or complete polyp retraction and mucous secretion. A similar response was observed after a 96-hour exposure to 100 ppm.

Thompson, in an undated report to the USGS, exposed Montastrea and Porites to used drilling fluids from a well of 4,200 m (13,725 ft) drilling depth. The corals were buried for eight hours under the fluid and then removed to a sand flat to observe recovery. The exposure produced tissue atrophy and decay, formation of loose strands of tissue, and expulsion of zooxanthellae (zooxanthellae are algae living within coral cells in a symbiotic relationship), all indicative of severe stress. The Montastrea colonies were dead 15 hours after removal, and the Porites colonies were dead after 10 days.

The effects of thin layer application to these species were also observed. In situ exposures of drilling mud produced no apparent effects on clearing rates; however, laboratory applica- tions did demonstrate effects. Applications of 10 ml thick carbonate sand or drilling fluid from a depth of either 4,200 m (13,800 ft) or 1,650 m (5,413 ft) were applied to the corals, with the following results:

- colonies in the sand experiment cleared themselves in 4 hours
- colonies in the 1,650 m fluid experiment cleared themselves in 2 hours
- colonies in the 4,200 m fluid experiment were 20 percent (Montastrea) and 40 percent (Porites) cleared after 4 hours, 20 percent (Montastrea) and 100 percent (Porites) cleared after 26 hours

Additional testing with Porites indicated that the 4,200 m fluid was more toxic than the 1,650 m fluid, probably because the use of additives increases with well depth. No data are available on actual drilling fluid composition, however.

Krone and Biggs (1980) exposed the coral (Madracis decactis) to suspensions of 100 ppm drilling mud from Mobile Bay, Alabama, which had been spiked with 0, 3, and 10 ppm ferrochrome lignosulfonate (FCLS). The drilling mud was presumably one with a low (< 1 ppm) FCLS concentration. The corals were exposed for 17 days, at which time they were placed in uncontaminated seawater and allowed to recover for 48 hours. All the corals exposed to the FCLS-spiked mud exhibited short-term increases in oxygen consumption and ammonia excretion. Photographic documentation of the corals revealed a progressive development of the following conditions: 1) a reduction in the number of polyps expanded indicating little or no active feeding; 2) extrusion of zooxanthellae; 3) bacterial infections with subsequent algal overgrowth; and 4) large-scale polyp mortality in two of the colonies. Coral behavior and condition improved dramatically during the recovery period. Polyps of surviving corals reexpanded and fed actively on day two of the recovery period.

Dodge (1982) evaluated the effects of drilling fluid exposure on the skeletal extension of reef-building corals (Montastrea annularis). Corals were exposed to 0, 1, 10, or 100 ppm drilling fluid ("Jay" fluid) for 48 days in a flow-through bioassay procedure. The drilling mud composition was changed approximately weekly as new mud taken from the well was added. One significant change in mud composition was in the diesel oil content, which was 0.4 percent by weight from the fourth week to the end of the experiment. Corals exposed to 100 ppm had significantly depressed linear growth rates and increased mortality. Calcification rates of corals exposed to 100 ppm decreased by 53 percent after four weeks and by 84 percent after six weeks. There was no indication of lowered growth rates for either the 1- or 10-ppm exposure.

Hudson and Robbin (1980) exposed corals (Montastrea annularis) to unused drilling fluid in heavy doses of two to four mm layers applied four times at 150-minute intervals. Drilling mud particles were generally removed by a combination of wave action, tentacle cleansing action, and mucus secretions. At the end of the exposure period, corals were placed in protected waters for six months. At the end of another six months, the corals were removed and examined for growth characteristics. Results of the growth analysis indicated that heavy concentrations of drilling mud applied directly to the coral surface over a period of only 7-1/2 hours reduced growth rates and suppressed variability. Trace element analyses of the corals indicated that neither barium nor chromium were incorporated into the skeletal materials.

Experiments with the coral Acropora cervicornis revealed reduced calcification rates after exposure to concentrations as low as 25 ppm of used Mobile Bay drilling mud (Kendall et al., 1983). Calcification rates in growing tips were reduced to 88, 83, and 62 percent of control values after 24-hour exposures to 25, 50, and 100 ppm (v/v) drilling mud, respectively. Effects on soluble tissue protein and ninhydrin positive substance were also noted at these or higher levels. Further experiments with kaolin, designed to reproduce the turbidity levels of the drilling mud without its chemical effects, revealed slight metabolic changes to the corals that were much less pronounced than those observed for the drilling mud treatments.

4.3.2.2 Stress Tests on Other Organisms

Other altered behavioral patterns in organisms have been noted after chronic exposures to drilling mud. Dock shrimp and dungeness crab larvae were exposed to 4,000 to 200,000 ppm barite and 4,000 to 100,000 ppm bentonite. The EC_{50} concentration inhibiting the swimming ability of half of the crab larvae ranged from 77,600 to 85,600 ppm bentonite, and was 71,400 ppm for barite. EC_{50}'s for shrimp larvae ranged from 13,800 to 34,600 ppm bentonite, and 5,400 to 50,400 ppm barite. Utilizing these results in conjunction with concentrations of barite and bentonite in lignosulfonate drilling fluids under the high energy Lower Cook Inlet mixing conditions, the "zone of toxicity" would extend only a few meters from the source (Houghton et al., 1981).

Conklin et al. (1980) studied the effects of barite on the grass shrimp (Palaemonetes pugio). They discovered that the mucus in the midgut of the shrimp has a high affinity to barite particles. During long-term exposure to barite, considerable quantities of mucus could be adsorbed to the barite and excreted. This phenomenon exposes midgut epithelial cells to the abrasive action of ingested barite particles and could lead to both necrosis and erosion of the epithelial cells.

Carr et al. (1980) exposed opossum shrimp (Mysidopsis) to the MAF of used lignosulfonate drilling fluid and observed the response of weight-specific respiration rates. Organisms in different life stages were exposed to various concentrations. Although respiration rates were nearly identical, average dry weights were significantly lower in exposed shrimp.

Neff et al. (1984) utilized a number of biochemical and physiological indices to detect pollutant stress in animals exposed to the settleable fraction of a water-based drilling fluid in situations including exposures of up to 119 days. This is reflective of the time it generally takes to drill 1-3 wells at a particular location. The following biochemical or physiological effects were noted: (1) there was a tendency for coelomic fluid glucose concentration to be lower in the worm Nereis virens exposed to the drilling mud settleable fraction than in controls, though the difference was statistically significant only at Day 14 of exposure; (2) after 14 days, net shell growth in experimental clams was significantly less than in controls (the authors note that it is uncertain whether the difference in growth was due to the 14-day exposure or to something during the pre-exposure period); (3) at 119 days the oxygen consumed to nitrogen excreted (O:N ratio) was slightly, but significantly, lower in experimental than in control clams; (4) the O:N ratios of sand shrimp, C. septemspinosa were slightly but not significantly lower in experimental than in control animals at both 4 and 14 days of exposure (the low O:N ratios indicate that protein is being utilized as a catabolic substrate, usually an indication of stress); (5) concentrations of two free amino acids in _N_. _virens_ and one free amino acid in _M_. _arenaria_ were significantly higher in experimental than in control animals; (6) mean taurine/glycine molar ratio was higher and the mean sum of threonine plus serine was lower in experimental than in control clams, suggesting that some of these animals were mildly stressed by exposure to the drilling mud settleable fraction; (7) in a set of experiments at day 90, liver glycogen concentrations in Class A and Class D flounder were significantly lower than those in corresponding controls, with a diet of drilling fluid- contaminated sandworms causing a slight depletion of liver glycogen reserves in winter flounder; the effect was more pronounced in larger than smaller fish; (8) lobsters that were exposed to sediments and food, which had been contaminated with settleable fraction of drilling mud, had the highest mean concentration of hepatopancreatic glucose plus glycogen.

Neff et al. (1984) note that the settleable fraction of water-based drilling mud resulted in "mild" stress as described above. They note, however, that this stress was not sufficient to affect growth of juvenile flounder and lobsters over the 99 to 119-day study period.

Atema et al. (1982) exposed lobster (_Homarus americanus_) to three test mixtures: used drilling fluids from Mobile Bay, Alabama; "Jay" fluids from a land-based drilling operation in Florida; and natural mud sediment from Buzzards Bay, Massachusetts. Water column and layered solid phase exposures were conducted for five-day periods, and behavioral changes noted. In water column exposures, no significant difference in mortality alone or organism damage alone was found, but when the mortality and damage groups were added, the Jay fluid had significantly greater effects than the Mobile Bay fluid or Buzzards Bay mud. Two molts occurred during the exposure period for most individuals. Time to first molt or number of molting organisms was not significantly different for the three substances. How- ever, for the second molt, the Jay fluid had significantly fewer molts than the Mobile Bay fluid or the Buzzards Bay mud.

Atema et al. (1982) also tested lobster preference to these same three media as substrates. Spontaneous tail flipping (a sign of stress) occurred in 29 drilling fluid exposures but only three controls, and the time required to build a shelter was twice as long for drilling fluid (59 minutes) than control substrates. These behavioral changes would presumably have a negative effect on lobster populations, causing the lobsters to be more exposed to predators.

Finally, these same researchers tested the effect various depths of drilling mud substrate had on lobster behavior, and noted that increasing substrate depth both increased the time before homesite construction would occur and decreased the quality of the shelters. They also noted that a 4 mm layer of a barite and bentonite mixture delayed shelter construction as much as actual drilling fluids, suggesting that physical effects alone can interfere with shelter building behavior.

Breteler et al. (1984) observed the behavior of three test species (the clam Mya arenaria, sandworm Nereis virens, and the grass shrimp Palaemonetes pugio) exposed to muds to which various amounts of mineral oil and diesel fuel had been added.

Effects of the muds on burrowing behavior were examined in solid phase bioassays. Only one replicate containing base mud (no oil additives) caused burrowing impairment among the worm, *Nereis*. With the exception of some impairment of burrowing in *Mya* during the second day of the bioassay, no visible behavioral abnormalities were observed among bioassay organisms during solid phase bioassays with drilling mud containing 0.5 percent mineral oil. However, low to moderate impairment of burrowing occurred in both *Mya* and *Nereis* during solid phase bioassays with drilling mud containing 5 percent mineral oil.

Sublethal effects were observed by Breteler et al. (1984) among *Nereis* and *Mya* exposed to solid phases of drilling mud containing either 0.5 percent or 5 percent low-sulfur diesel fuel. Moderate numbers of *Nereis* failed to burrow during the first stage of exposure at the 0.5 percent level, while most worms were exposed on the surface at the 5 percent level. However, within four days, all worms were burrowing. Still, impaired burrowing behavior persisted throughout the bioassay in moderate numbers of *Mya* at low and high levels of this diesel fuel additive. More severe sublethal effects were observed in the solid phase tests involving high-sulfur diesel fuel. Moderate to high levels of impaired burrowing were evident among *Nereis* and *Mya* as a result of exposure to the solid phase prepared from drilling mud containing 0.5 percent of this additive.

A sublethal response in shrimp also was observed by Breteler et al. (1984) at the initiation of the solid phase tests. Upon addition of test material to the tanks, the water was very turbid and had a brownish appearance. Shrimp exhibited avoidance responses by swimming against the glass walls of the aquarium.

In a companion study Neff et al. (1984) observed that introduction of the settleable fraction into the treatment aquarium provoked immediate and strong, but short-lived, reactions in fish, scallops, and shrimp. Shrimp and fish first tried to avoid the plume of settling drilling fluid and then congregated near the water surface after they were enveloped by the plume. This behavioral pattern persisted for 2-3 hours after introduction of drilling fluid. Normal behavior resumed after drilling fluid solids settled. Scallops exhibited increased swimming activity with the introduction of drilling fluid.

Individual components of drilling mud (e.g., chromium) may also be toxic. For discussions of known toxicity information on the 129 "priority pollutant" metals and organics pollutants, see EPA (1980a). Consideration of individual toxicities may not, however, be sufficient to predict the effects of exposure in the field to mixtures as complex as drilling mud.

4.3.3 Community Recruitment and Development

A limited number of studies analyzed the effects of whole drilling fluids or components on community recruitment and development. One set of these studies introduced planktonic larvae of several species into a flow-through system and allowed them to settle on either a sand/drilling fluid mixture, a sand bottom covered with a thin drilling fluid layer, or a plain sand bottom for the control group. Organisms were counted after 8 to 10 weeks.

Tagatz et al. (1982) used estuarine macrobenthic organisms and found abundance significantly decreased by concentrations of 50 ppm drilling mud. They also found rank correlation of species abundance and species diversity altered by a Mobile Bay drilling mud treatment. Previous work by these same researchers had shown whole used mud or barite to have a detrimental effect on recruitment (Tagatz et al., 1980). Annelids, and to a lesser degree, coelenterates and mollusks, were all significantly affected by the experimental treatment. The authors concluded that drilling fluid could significantly affect recruitment and possibly change the structure of the food web.

Annelids were most affected by barite, and a 5 mm barite layer over sand had more impact than the barite-sand mixture. Mollusc abundance was significantly reduced only in the aquaria with the barite layer over sand (Cantelmo et al., 1979). This indicates that there is a physical as well as a chemical factor inhibiting recruitment. Analysis of meiofaunal communities under these same conditions showed significant increases in total density (101 percent) and the density of nematodes (112 percent) for the 1:11 barite and sand mixture. The 1:4 barite and sand mixture showed insignificant density increases, and the barite cover reduced nematode and copepod densities below the control and the 1:11 and 1:4 barite and sand mixtures.

These studies are difficult to interpret with regard to actual field conditions, however. Only a few species contributed to the observed effects. However, they do suggest that drilling fluid discharges can alter benthic communities within the zone of heavy deposition by influencing larval recruitment.

4.4 ACUTE TOXICITY OF PRODUCED WATER

A limited number of studies have examined the toxicity of produced waters. A bioassay program was carried out by Rose and Ward (1981) on produced water from the Buccaneer Field in the Gulf of Mexico off Texas (Table 4-13). Results were presented for four series of test conditions. Test series Nos. 1-3 were performed at a shore-based laboratory, while test series No. 4 was conducted on the production platform. The majority of tests were performed for series No. 1; these tests were conducted at a shore-based laboratory and the media was either aerated or naturally maintained above a dissolved oxygen (DO) concentration of 4 mg/l. The 96-hour LC_{50} value for this series ranged between 8,000 and 408,000 ppm, the lowest (most toxic) value being obtained for larval brown shrimp.

In series No. 2 (conducted at a shore-based laboratory), the test media were not maintained above 4 mg/l DO and the LC_{50} values were lower than those for the same species tested in aerated media. For test series No. 3, flow-through bioassays were conducted in the laboratory and again the media were aerated, while in test series No. 4, flow-through tests were performed on the platform with aerated media. All brine samples during this phase had been treated with acrolein, a highly reactive biocide that was scavenged with ammonium bisulfite before discharge. The chemical was not detected in any of the samples.

Rose and Ward (1981) also compared their results with a previous study of toxicity of produced water from the Buccaneer Field (Zein-Eldin and Keney, 1978). This earlier evaluation, which also addressed the toxicity of produced water without

Table 4-13 MEDIAN LETHAL CONCENTRATIONS (LC_{50}'s) AND ASSOCIATED 95% CONFIDENCE INTERVALS FOR ORGANISMS ACUTELY EXPOSED TO FORMATION WATER UNDER VARIOUS EXPERIMENTAL CONDITIONS, (ROSE & WARD, 1981).

Organism	Season of test	Formation water used	Testing temp.	$LC_{50}^{a,b}$	95% Confidence interval[a,b]
Test Series No. 1[c]					
Brown shrimp					
Larva	Spring 1979	D	28	10,000	7,000-15,000
		E	28	12,000	9,000-18,000
		F	28	8,000	6,000-12,000
		G	28	8,000	5,000-11,000
Subadult	Summer 1978	A	25±1	94,000	63,000-172,000
	Fall 1978	B	22±1	60,000	0-100,000
	Winter 1979	C	18±2	183,000	130,000-279,000
	Spring 1979	D	24±1	61,000	47,000-76,000
Adult	Summer 1978	A	25±1	94,000	63,000-172,000
	Fall 1978	B	22±1	78,000	38,000-183,000
	Winter 1979	C	18±2	178,000	132,000-240,000
	Spring 1979	D	24±1	90,000	61,000-156,000
White Shrimp					
Subadult	Summer 1978	A	25±1	56,000	51,000-62,000
	Fall 1978	B	22±1	61,000	48,000-76,000
	Winter 1979	C	18±1	133,000	67,000-366,000
Adult	Summer 1978	A	25±1	81,000	48,000-153,000
	Fall 1978	B	22±1	62,000	27,000-110,000
	Winter 1979	C	18±1	92,000	58,000-150,000
	Spring 1979	D	24±1	37,000	24,000-52,000
Barnacle	Summer 1978	A	25±1	33,000	25,000-38,000
	Fall 1978	B	22±1	84,000	68,000-104,000
	Winter 1979	C	18±2	154,000	111,000-222,000
	Spring 1979	D	24±1	60,000	49,000-71,000
Crested	Summer 1978	A	25±1	158,000	100,000-320,000
blenny	Fall 1978	B	22±1	408,000	320,000-560,000
	Spring, 1979	D	24±1	178,000	135,000-235,000
Test Series No. 2[d]					
Barnacle	Winter 1979	C	18±2	8,000	5,000-13,000
Cr. blenny	Spring 1979	D	24±1	7,000	5,000-12,000
Test Series No. 3[e]					
White shrimp					
Subadult	Fall 1978	B	22±1	62,000	48,000-76,000
Test Series No. 4[f]					
Brown shrimp					
Subadult	Spring 1979	H	25-29	44,000	25,000-60,000
Barnacle	Spring 1979	H	25-29	51,000	34,000-68,000

Table 4-13 MEDIAN LETHAL CONCENTRATIONS (LC_{50}'s) AND ASSOCIATED 95% CONFIDENCE INTERVALS FOR ORGANISMS ACUTELY EXPOSED TO FORMATION WATER UNDER VARIOUS EXPERIMENTAL CONDITIONS, (ROSE & WARD, 1981).
(Continued)

[a] All LC_{50}'s and associated 95% confidence intervals are 96-hr values except in the case of larval brown shrimp, for which 48-hr values are reported. Units are ppm formation water.

[b] In most cases, LC_{50}'s and related confidence intervals were calculated by the moving average method. However, the binomial method was employed in Test Series No. 1 for subadult brown shrimp tested in the fall as well as for crested blennies tested in the summer and fall. The probit method was used for Test Series No. 4.

[c] Static laboratory tests; oxygen demand of formation water not evaluated. Except in the case of tests with larval brown shrimp, test and control media were aerated to maintain dissolved oxygen concentration (DO) above 4 mg/l. Aeration was not required to maintain a DO above 4 mg/l in tests with larval shrimp.

[d] Static laboratory tests; oxygen demand of formation water evaluated. Test and control media were not aerated. Although DO of control media remained above 4 mg/l during the tests, DO of test media decreased to 0.5-3.2 mg/l (barnacle) and 1.2-4.0 mg/l (crested blenny) by the end of the 96-hr testing period.

[e] Flow-through laboratory tests; oxygen demand of formation water not evaluated. Test and control media were aerated to maintain DO above 4 mg/l.

[f] Flow-through platfom tests; oxygen demand of formation water not evaluated. Test and control media were aerated to maintain DO above 4 mg/l.

considering oxygen demand, generated two sets of 96-hour LC_{50} values for juvenile white shrimp. In the first set, 96-hour LC_{50} values of 1,850 - 6,500 ppm were obtained for produced water treated with two biocides (K-31 and KC-14) that were not scavenged. The second set of values was obtained for produced water without the addition of biocides; these LC_{50} values exceeded 100,000 ppm.

Rose and Ward (1981) suggested that the operator's current practice of treating produced water with biocide (acrolein and the scavenger, ammonium bisulfite) is more environmentally protective than the previous practice (K-31 or KC-14 without scavenger) and less environmentally protective than discharging untreated produced water. The toxic effects of biocides in produced waters were also observed by Workman and Jones (1979). They found that blennies kept in cages below the produced water discharge pipe of a production platform in the Buccaneer Field suffered no mortalities when the effluent had not been treated with biocide, but approximately half of the blennies died (within 48 hours) when biocides were used. (The type and concentration of biocide was not documented.)

Middleditch (1984) also noted that divers working near the produced water discharge from Buccaneer Field experienced occasional eye and skin irritation when the biocide acrolein was being used. Middleditch noted that acrolein is routinely "scavenged" by converting it to a bisulfite adduct, but that this reaction is reversible; even though free acrolein may not be detected in the effluent, it may be released after discharge.

Because most of the laboratory bioassays cited above were performed on media that were aerated and open to air, the volatile hydrocarbons present in the produced waters may have been lost as has been observed by Rice et al. (1979). As noted in Section 2, the concentrations of volatile liquid hydrocarbons in produced water from the Buccaneer Field were on the order of 21 ppm, 80 percent of which were the more toxic aromatics. In the above cited bioassays, an undetermined amount of these hydrocarbons may have been lost during the collection and transport of samples and as a result of subsequent aeration.

Studies on the water-soluble fractions (WSF) of oil have provided information that is helpful in evaluating the acute lethal toxicity of produced water. WSFs contain fractions of hydrocarbons similar to those found in produced water (i.e., the more soluble aromatic hydrocarbons). For example, undiluted WSF of Cook Inlet crude oil contains about 7 ppm of aromatic hydrocarbons. Rice et al. (1979) examined the toxicity of WSF of Cook Inlet crude oil to 39 Alaskan marine species. Pelagic fish and shrimp were the most sensitive to the WSFs of crude oil with 96-hour LC_{50} values from 1-3 ppm total aromatics (~140,000-430,000 ppm WSF). Rice et al. estimated that concentrations of aromatic hydrocarbons in the WSF declined over the 96-hour test period, by evaporation and biodegradation, to about 20 percent of the initial concentrations. Rice et al. (1981) found similar levels of toxicity (100,000 - 400,000 ppm) for ballast-water treatment effluent at Port Valdez, Alaska. They noted that the effluent contained light aromatics in the 1-16 ppm range, similar to the levels observed in produced waters (Section 2).

The available information suggests that the acute toxicity of produced water without the addition of biocides is low. Toxicity that is present may be related to the light aromatic hydrocarbons. However, a problem with assessing this toxicity is the loss of the hydrocarbons during the course of the exposure period. When biocides are present as in the tests conducted by Zein-Eldin and Keney (1978), the toxicity of produced water may be greatly increased. This toxicity may be reduced if the biocide is scavenged prior to discharge as in the tests conducted by Rose and Ward (1981). However, there is also evidence that this process may be reversed subsequent to discharge (Middleditch, 1984).

4.4.1 Chronic and Sublethal Toxicity of Produced Waters

Although the acute toxic effects of produced water appear to be low (when biocides are absent), chronic lethal and sublethal effects must be considered. Such effects are expected to occur at concentrations below those that are acutely toxic. Chronic exposures to organisms in the water column could occur in areas where the hydrocarbons discharged to the water column are not rapidly removed from the system and where there is a continuous input. The potential for build-up of hydrocarbons in the water column would be greater in semi-enclosed coastal embayments with limited flushing than in offshore regions. However, the rate of dilution, advection, and other losses such as evaporation and sedimentation would have to be considered before judging whether chronic effects on water column organisms could occur.

Hydrocarbons that have become associated with the sediments are a more likely cause of chronic exposure. A number of studies have indicated that petroleum hydrocarbons can become incorporated into the sediments (NAS, 1975; Armstrong et al., 1977, API, 1977; Gearing et al., 1979). Studies have also suggested that the lighter molecular weight hydrocarbons (the major hydrocarbon fraction in produced water) are lost more rapidly from sediments than the higher molecular weight compounds. However, because produced water may be discharged continuously, lighter as well as higher molecular weight hydrocarbons have the potential for accumulating in the sediment and exerting effects on benthic organisms.

Chronic lethal or sublethal effects of produced waters can result from soluble petroleum hydrocarbon concentrations on the order of a few parts-per-billion (µg/l) or less. For example, although small amounts of oil (200 µ/l or less) apparently stimulated growth of juveniles of the alga Fucus endentatus, Steele (1972) found that even at the lowest concentration of oil tested (0.2 µg/l) no fertilization of this alga occurred, and the eggs lost viability and completely disintegrated by the sixth day of the experiment. Other experiments involving large enclosed water columns (4.8 m diameter x 20 m deep) were used to examine the chronic effects of low concentrations of oil to various planktonic organisms in the field (Davies et al., 1981). Copepods proved very sensitive to an effluent water containing 5-15 µg/l of oil. Davies et al. (1981) reported that all components of the tested zooplankton bottom invertebrates, Oithona, other copepods and naupliar stages seem to be sensitive to effluent produced water at dilution of 1:700.

A general sublethal effect of hydrocarbons is narcosis. For example, Sanborn and Malins (1977) observed narcotization of larval spot shrimp (Pandalus platyceros) and Dungeness crab (Cancer magister) zoeae exposed to 8 to 12 μg/l naphthalene.

Animal behavior can also be affected at low concentrations. For example, Atema and Stein (1974) found that low levels of oil could affect the behavior of foraging lobsters (Homarus americanus). At a measured hydrocarbon concentration of 17.2 μg/l, there was a doubling of the time period between noticing and pursuing food by lobsters. Reproductive behavior of certain crabs may also be impaired at soluble oil concentrations below 10 μg/l (Takahashi and Kittredge, 1973). The studies of Takahashi and Kittredge (1973) and Jacobson and Boylan (1973) also indicate that low concentrations of aromatic hydrocarbons - on the order of 1 μg/l can disrupt the responses of crabs and snails to chemical substances that normally initiate feeding behavior. Burrowing activities of the clam Macoma balthica were affected by water soluble fractions of Prudhoe Bay crude oil: at a concentration of 36 μg/l and an exposure period of 9 days, many of the buried clams came to the sediment surface.

The above information indicates that chronic lethal and sublethal effects can occur at concentrations on the order of a few parts-per-billion of soluble hydrocarbons, particularly aromatics. While numerous examples of threshold responses at much higher concentrations can be found, it is clear that concentrations on the order of 1 μg/l (and perhaps even less) will have effects on some marine biota.

Some produced water also contains dissolved hydrogen sulfide (H_2S). For example, produced water from fields in the Santa Barbara Channel can contain a few hundred mg/l H_2S. This chemical can be toxic to marine organisms.

There are phylogenetic and habitat-related correlations to H_2S tolerances (Theede et al., 1969). In general, marine and freshwater invertebrates have a much higher resistance than freshwater fish. (No information on tolerance of marine fish to H_2S was found during an initial search of the literature). Polychaetes and many bivalves show the highest resistance among invertebrates tested in experimental and field situations. This phylogenetic pattern to H_2S tolerance appears related to a group's capabilities for facultative anaerobiosis (Caldwell 1975; Theede et al., 1969). Sedentary organisms appear more tolerant than active species.

The acute toxicity levels of H_2S have been seen in the range of 0.02 to 40 mg/l in invertebrates and 0.04 to 1 mg/l in freshwater adult fish (Adelman and Smith, 1970; Caldwell, 1975; Dimov et al., 1970; Henriksson, 1969; Theede et al., 1969; Smith et al., 1976).

Low concentrations of H_2S in water (as low as 0.01 mg/l) may adversely affect fish fry survival (Adelman and Smith, 1970; Smith et al., 1976). These observations were made with freshwater fish; as already noted, no data were found for marine fish.

Invertebrate reproduction is also sensitive to H_2S. For example, when fertilized oyster gametes were transiently exposed to H_2S, larval development was reduced (Caldwell 1975). A two-hour exposure to 0.3 mg/l H_2S led to an approximately 60 percent reduction in normal larval development.

4.4.2 Toxicity of Chemical Components of Produced Water

Given the limited amount of toxicity data for produced waters, it is useful to examine available toxicity data for produced water constituents. Such an examination would not, of course, account for possible synergistic effects among these constituents in whole fluids. Nonetheless, this approach may serve to expand an understanding of the major components of produced water toxicity.

Table 4-14 presents available toxicity data for whole produced waters and individual trace metal and hydrocarbon constituents. Table 4-15 shows the measured range of concentration of each pollutant in undiluted produced water, and indicates which acute toxicity values may be exceeded by the discharge concentrations for the species listed. Mean discharge concentrations for zinc and phenol exceed at least one of the LC_{50} values for Mercenaria mercenaria and Stolephorus purperens, respectively.

Another way of using constituent data to assess produced water toxicity is to compare the data with EPA's water quality criteria for the protection of marine life and human health. This is done in Table 4-16 and indicates that exceedances of most of the criteria would occur for the highest reported undiluted concentrations in produced water.

TABLE 4-14 ACUTE LETHAL TOXICITY OF PRODUCED WATERS AND CONSTITUENTS OF PRODUCED WATERS TO MARINE ORGANISMS

(96-hr LC_{50}/EC_{50} unless otherwise noted)

Constituent/Species	Life stage	LC_{50}/EC_{50}(ppm)	Reference
a. Produced waters			
Whole produced waters			
Balanus tintinnabulum (Barnacle)[a]	Adult	83,000	N.M.F.S., 1980
Penaeus aztecus (Brown shrimp)[a]	Adult	116,000	N.M.F.S., 1980
	Adult	78,000-178,000	Rose & Ward, 1981
	Subadult	60,000-183,000	Rose & Ward, 1981
	Larvae	9,500 (48-hr LC50)	N.M.F.S., 1980
	Larvae	8,000-12,000 (48-hr LC50)	Rose & Ward, 1981
Penaeus setiferus (White shrimp)[a]	Adult	70,000	N.M.F.S., 1980
Hypleurochilus geminatus (Crested blennie)[a]	Adult	269,000	N.M.F.S., 1980
	Adult	158,000-408,000	Rose & Ward, 1981
Cyprinodon variegatas (Sheepshead minnow)	Adult	550,000-600,000	Andreason & Spears, 1983
b. Trace metals			
Zinc			
Capitella capitata (Polychaete)	Adult	3.5	U.S. EPA, 1980
	Larvae	1.7	U.S. EPA, 1980
Neanthes arenaceodentata (Polychaete)	Adult	1.8	U.S. EPA, 1980
	Juvenile	0.9	U.S. EPA, 1980
Nereis diversicolor (Polychaete)	Adult	11-55	U.S. EPA, 1980
Nereis virens (Sand worm)	Adult	8.1	U.S. EPA, 1980
	Adult	2.6 (168-hr LC50)	U.S. EPA, 1980
Ophryotrocha labronica (Polychaete)	Adult	1.0 (13-hr LC50)	U.S. EPA, 1980
Crassostrea virginica (American oyster)[a]	—	0.31	U.S. EPA, 1980
	Larvae	0.75 (48-hr LC0)	U.S. EPA, 1980
	Larvae	0.50 (48-hr LC100)	U.S. EPA, 1980
Mercenaria mercenaria (Hard-shelled clam)	—	0.17	U.S. EPA, 1980
	Larvae	0.20 (10-day LC50)	U.S. EPA, 1980
	Larvae	0.05-0.34 (12-day LC5-LC95)	U.S. EPA, 1980
	Embryo	0.28 (48-hr LC100)	U.S. EPA, 1980

TABLE 4-14 ACUTE LETHAL TOXICITY OF PRODUCED WATERS AND CONSTITUENTS OF PRODUCED WATERS TO MARINE ORGANISMS

(96-hr LC_{50}/EC_{50} unless otherwise noted)
(Continued)

Constituent/Species	Life stage	LC_{50}/EC_{50} (ppm)	Reference
Mya arenaria (Soft-shelled clam)	—	5.2-7.2	U.S. EPA, 1980
	Adult	1.5-3.1 (168-hr LC50)	U.S. EPA, 1980
Mytilus edulis (Mussel)	—	2.5-4.3	U.S. EPA, 1980
Nassarius obsoletus (Mud snail)	Adult	50.0	U.S. EPA, 1980
	Adult	7.40 (168-hr LC50)	U.S. EPA, 1980
Acartia clausi (Copepod)	Adult	0.95	U.S. EPA, 1980
Acartia tonsa (Copepod)	Adult	0.29	U.S. EPA, 1980
Eurytemora affinis (Copepod)	Adult	4.09	U.S. EPA, 1980
Nitocra spinipes (Copepod)	Adult	1.45	U.S. EPA, 1980
Pseudodiaptomus coronatus (Copepod)	Adult	1.78	U.S. EPA, 1980
Tigriopus japonicus (Copepod)	Adult	2.16	U.S. EPA, 1980
Mysidapsis bahia (Mysid shrimp)	—	0.50	U.S. EPA, 1980
Mysidopsis bigelowi (Mysid shrimp)	—	0.59	U.S. EPA, 1980
Homarus americanus (Lobster)[b]	Larvae	0.18-0.58	U.S. EPA, 1980
Carcinus maenas (Crab)	Larvae	1.0	U.S. EPA, 1980
Pagurus longicarpus (Hermit crab)	Adult	0.4	U.S. EPA, 1980
	Adult	0.2 (168-hr LC50)	U.S. EPA, 1980
Asterias forbesi (Starfish)	Adult	39.0	U.S. EPA, 1980
	Adult	2.3 (168-hr LC50)	U.S. EPA, 1980
Fundulus heteroclitus (Mummichog)	Adult	60	U.S. EPA, 1980
	Adult	60 (96-hr LC28)	U.S. EPA, 1980
	Adult	10.0-20.0 (168-hr LC50)	U.S. EPA, 1980
	Adult	157 (48-hr LC100)	U.S. EPA, 1980
	Adult	43 (192-hr LC0)	U.S. EPA, 1980
	Adult	66 (192-hr LC50)	U.S. EPA, 1980
	Larvae	83	U.S. EPA, 1980
Menidia menidia (Atlantic silverside)	Larvae	2.73-4.96	U.S. EPA, 1980

TABLE 4-14 ACUTE LETHAL TOXICITY OF PRODUCED WATERS AND CONSTITUENTS OF PRODUCED WATERS TO MARINE ORGANISMS
(96-hr LC_{50}/EC_{50} unless otherwise noted)
(Continued)

Constituent/Species	Life stage	LC_{50}/EC_{50}(ppm)	Reference
Pseudopleuronectes americanus (Winter flounder)[b]	Larvae	4.92-18.2	U.S. EPA, 1980
c. Hydrocarbons			
Petroleum alkanes			
Crassostrea virginica (American oyster)[a]	Adult	33-154	Brook et al., 1980
Penaeus aztecus (Brown shrimp)[a]	Subadult	56-133	Brooks et al., 1980
Penaeus duorarum (Pink shrimp)[a]	Subadult	56-133	Brooks et al., 1980
Penaeus setiferus (White shrimp)[a]	Adult	37-92	Brooks et al., 1980
Benzene			
Crassostrea gigas (Pacific oyster)	—	924	U.S. EPA, 1980
Tigriopus californicus (Copepod)	—	450	U.S. EPA, 1980
Nitocra spinipes (Copepod)	—	82-111 (24-hr LC50)	U.S. EPA, 1980
Crago franciscorum (Bay shrimp)	—	17.6	U.S. EPA, 1980
Palaemonetes pugio (Grass shrimp)	—	27	U.S. EPA, 1980
	Adult	33.5-40.8 (24-hr LC50)	U.S. EPA, 1980
	Larvae	74.4-90.8 (24-hr LC50)	U.S. EPA, 1980
Cancer magister (Dungeness crab)	Larvae	108	U.S. EPA, 1980
Morone saxtilis (Striped bass)	—	5.1-10.9	U.S. EPA, 1980
Toluene			
Nitocra spinipes (Copepod)	—	24.2-74.2 (24-hr LC50)	U.S. EPA, 1980
Crassostrea gigas (Pacific oyster)	—	1,050	U.S. EPA, 1980
Mysidopsis bahia (Mysid shrimp)	—	56.3	U.S. EPA, 1980
Crago franciscorum (Bay shrimp)	—	3.7	U.S. EPA, 1980

(Continued)

TABLE 4-14 ACUTE LETHAL TOXICITY OF PRODUCED WATERS AND CONSTITUENTS OF PRODUCED WATERS TO MARINE ORGANISMS

(96-hr LC$_{50}$/EC$_{50}$ unless otherwise noted)
(Continued)

Constituent/Species	Life stage	LC$_{50}$/EC$_{50}$ (ppm)	Reference
Palaemonetes pugio (Grass shrimp)	—	9.5	U.S. EPA, 1980
	Adult	17.2-38.1 (24-hr LC50)	U.S. EPA, 1980
	Larvae	25.8-30.6 (24-hr LC50)	U.S. EPA, 1980
Oncorhynchus kisutch (Coho salmon)	—	10-50	U.S. EPA, 1980
Cyprinodon variegatus (Sheepshead minnow)	—	277-485	U.S. EPA, 1980
Morone saxatilis (Striped bass)	—	6.3	U.S. EPA, 1980
Oncorhynchus gorbuscha (Pink salmon)	fry	5.4	Thomas & Rice, 1979
Phenol			
Palaemonetes pugio (Grass shrimp)	—	5.8	U.S. EPA, 1980
Crassostrea virginica (Eastern oyster)[a]	—	58.2	U.S. EPA, 1980
Mercenaria mercenaria (Hard clam)	—	52.6	U.S. EPA, 1980
Kuhlia sandvicensis (Mountain bass)	—	11	U.S. EPA, 1980
Salmo gairdneri (Rainbow trout)	—	6.9 (48-hr LC50)	U.S. EPA, 1980
Stolephorus purpureus (Nehu)	—	0.51 (12-hr LC50)	U.S. EPA, 1980
Naphthalene			
Neanthes arenaceodentata (Polychaete)	—	3.8	U.S. EPA, 1980
Crassostrea gigas (Pacific oyster)	—	199	U.S. EPA, 1980
Palaemonetes pugio (Grass shrimp)	—	2.6 (24-hr LC50)	U.S. EPA, 1980
		2.4	U.S. EPA, 1980
Penaeus aztecus (Brown shrimp)[a]	—	2.5 (24-hr LC50)	U.S. EPA, 1980
Cyprinodon variegatus (Sheepshead minnow)	—	2.4 (24-hr LC50)	U.S. EPA, 1980
Oncorhynchus gorbuscha (Pink salmon)	fry	0.9 (24-hr LC50)	Thomas & Rice, 1979

[a] Species distribution data in NOAA data base for commercially important species in the Gulf of Mexico.

[b] Species distribution data in NOAA data base for commercially important species in the Atlantic OCS.

TABLE 4-15 ACUTE LETHAL TOXICITY VALUES (LC_{50}/EC_{50}) WHICH MAY BE EXCEEDED BY MEASURED DISCHARGE CONCENTRATIONS OF POLLUTANTS IN PRODUCED WATERS

Pollutant	Discharge concentrations (ppm)[a] Range (mean)	Species	LC_{50}/EC_{50} (ppm)[b]
Zinc	0.005–0.519 (0.168)	*Crassostrea virginica*	0.31
			0.50 (48-hr LC_{100})
		Mercenaria mercenaria	0.17
			0.20 (10-day LC_{50})
			0.05–0.34 (12-day LC_{50})
			0.28 (48-hr LC_{100})
		Acartia tonsa	0.29
		Mysidopsis bahia	0.50
		Homarus americanus	0.18–0.58
		Pagurus longicarpus	0.4
			0.2 (168-hr LC_{50})
Benzene	0.002-12.2 (2.98)	*Morone saxatilis*	5.1-10.9
Toluene	0.060-19.8 (2.07)	*Crago franciscorum*	3.7
		Palaemonetes pugio	9.5
			17.2-38.1 (24-hr LC_{50})
		Oncorhynchus kisutch	10-50
		Oncorhynchus gorbuscha	5.4
		Morone saxatilis	6.3
Phenol	0.065-20.8 (2.34)	*Palaemonetes pugio*	5.8
		Kuhlia sandvicensis	11
		Salmo gairdneri	6.9 (48-hr LC_{50})
		Stolephorus purpurens	0.51 (12-hr LC_{50})
Naphthalene	0.019-1.45 (0.187)	*Oncorhynchus gorbuscha*	0.92 (24-hr LC_{50})

[a] Discharge concentrations from the 30-platform study (EPA, 1983).

[b] 96-hr LC_{50} (EC50) assumed unless otherwise noted.

TABLE 4-16 COMPARISON OF CONCENTRATIONS OF CONSTITUENTS OF PRODUCED WATER WITH AVAILABLE WATER QUALITY CRITERIA FROM OFFSHORE OIL AND GAS FACILITIES

Pollutant	Range (mean) of discharge concentrations	Criteria for protection of µg/l: Saltwater aquatic life		
		Chronic	Acute	Human health ingestion of organisms
Benzene	2-12,150 (2,977)	700 C	5,100 A	400 at 10^{-5} 40 at 10^{-6} 4 at 10^{-7}
Ethylbenzene	6-6,010 (431)	—	430 A	3,280
Naphthalene	19-1,454 (187)	100 C[a]	2,350 A	—
Phenol	65-20,812 (2,343)	—	5800 A	769,000
Toluene	60-19,800 (2,007)	3,910 C[b]	6,300 A	424,000
2,4-Dimethylphenol	1-3,504 (200)	--	--	--
Zinc	5-519 (168)	58	170	--

Abbreviations: C = Chronic effects noted; no proper criterion.
A = Acute effects noted; no proper criterion.

[a] Lowest reported chronic aquatic effects data from Anderson, 1979.

[b] Lowest reported chronic aquatic effects data from Thomas and Rice, 1979.

5.0 FIELD STUDIES

5.1 SUMMARY

5.1.1 Studies around Drilling Operations

Field studies to determine the effects of drilling fluid discharges on surrounding biota have been conducted in the Mid-Atlantic, North Atlantic (Georges Bank), Lower Cook Inlet and Beaufort Sea in Alaska, and Tanner Bank, California. The sampling design of all but two of these studies limited the assessment to detection of major changes. These studies have only examined alterations resulting from exploratory (i.e., one well) operations or limited bulk discharges. No such data on biological effects exist for multiple well activities during drilling operations.

The most effective way to monitor the biological effects of drilling discharges is to take quantitative samples of the benthic infauna - animals that live on the sea floor. Sample variability is typically lower than that for planktonic or pelagic communities and thus sampling precision is higher. These animals do not move much, if at all, so they are much more vulnerable to the particulate fraction of fluids that accumulates on the bottom. The most common approach is to take replicate quantitative samples and determine whether there have been changes in species richness, species composition, or abundance. With six replicate samples it is possible to detect changes of 15-25 percent of the mean for numbers of species and 25-50 percent changes in the mean abundances of some individual species.

Only two of the field studies used such an approach: the mid-Atlantic study and the Georges Bank study. The resolution for detecting change in marine communities was considerably lower in each of the remaining studies. These studies probably were incapable of detecting statistically significant changes of 100 percent or perhaps even greater.

5.1.1.1 Effects on Biota

Benthic studies in high energy environments (Lower Cook Inlet, Georges Bank) have shown no substantial effects on benthic biota. There was a significant general increase in the number of species and densities during the four-month period of the Cook Inlet study. Sites near the drilling operation, however, showed decreases in several community parameters relative to control sites. The authors concluded that no drilling related effects were observed. However, spatial temporal variability and a change in sampling design precludes the detection of measurable changes. In the Georges Bank study there were seasonal changes in some species abundances. In at least one case, these changes were correlated with alterations in sediment grain size. Accumulations of cuttings may have contributed to these changes, but it is also known that the sea floor on Georges Bank is scoured by winter storms.

The mid-Atlantic study was conducted in a lower energy environment. The abundance of fish and decapods increased in the vicinity of the well, possibly due to increased micro relief provided by the cuttings pile or food availability. Sessile megabenthos were subjected to burial. Densities of major taxa decreased between the pre-drilling and first post-drilling survey. There was some recovery after a one-year period. These changes were also reported at the one-mile and two-mile stations, but because of annual variation, it was not possible to determine whether or not those stations were within or beyond the zone of influence.

5.1.1.2 Metals and Hydrocarbons in Sediments

Numerous studies have established sediment barium and trace metal gradients around drilling sites. In the mid-Atlantic study, all one-mile and one of the two-mile stations sampled in both post-drilling surveys had elevated sediment barium levels. On the southern flank at Georges Bank at 140 m depth, there was an increase of barium from 30 to 107 ppm within a 200 m zone and a smaller increase was detected at 2,000 m. On Georges Bank at 60 m depth, barium increased from 37 to 67 ppm within a few hundred meters at the drilling site, and smaller increases were detected up to six km distance. Elevated levels of other metals such as arsenic, cadmium, chromium, lead, mercury, nickel, vanadium, and zinc were found near the rig site in one or more of the above studies.

There have been very few attempts to evaluate hydrocarbon accumulation in sediments as a result of exploratory drilling discharges. On Georges Bank aromatic hydrocarbon levels were extremely low, and essentially constant over time. There are reports of hydrocarbons in sediments around production platforms (see Section 3), but it is impossible to determine the relative contribution from drilling muds versus produced waters.

5.1.1.3 Bioaccumulation of Metals and Hydrocarbons

In the Beaufort Sea study there was some evidence of accumulation of mercury but not of other metals. Barium levels were not determined. In the mid-Atlantic study, increases in tissue levels of barium were detected in the first post-drilling study (conducted shortly after the termination of drilling operations), but had returned to pre-drilling levels after one year. Chromium concentrations were elevated during the second post-drilling study. There was no evidence of accumulation of metals in tissue in the higher energy environments of Georges Bank and Cook Inlet.

5.1.2 Studies Around Production Platforms

A number of field studies have been conducted to examine the environmental effects of production operations. The characteristics of five major studies are presented in Table 5-1. These field studies are generally useful for evaluating the chemical, biological, or physical parameters that are being modified by operations related to production platforms.

It is more difficult to assess impacts over a greater area. Such studies have been performed in regions that have already experienced a number of years of production activity as well as relatively large effects from other sources of contamination such as the input of the Mississippi to the Gulf of Mexico, tanker discharges, and atmospheric inputs. In addition, because areas around production operations have experienced discharges from drilling operations, there are confounding factors related to sorting the effects of produced water from those from drilling mud and cuttings.

TABLE 5-1 CHARACTERISTICS OF SELECTED FIELD STUDIES CONDUCTED AROUND PRODUCTION OPERATIONS

STUDY	GENERAL CHARACTERISTICS
Central Gulf of Mexico Platform Study (Southwest Research Institute, 1981)	Four primary and 16 secondary platforms were examined on Lousiana OCS west of Mississippi delta. Platforms were located 5-120 km offshore in 6-75 m depths. The influence of the Mississippi made it difficult to sort out the effects attributable solely to platform operations.
Buccaneer Field Study, Gulf of Mexico (Middleditch, 1981)	The Buccaneer Field facilities, which consist of two production platforms had been in operation for 15 yearS at the time of the study. The field is located 50.5 km south of Galveston, TX in a water depth of 20 m. Based on sediment and physical oceanographic studies, the area appeared to be a relatively high-energy environment.
Trinity Bay Study, Gulf of Mexico (Armstrong et al. 1977)	Trinity Bay is an estuarine area along the coast of Texas and has a water depth of approximately 2.5 m. Sediments are of a silt-clay nature and the water is turbid. Produced water is discharged one meter from the bottom.
Offshore Ecological Investigation (Morgan et al. 1974; Bender et al. 1979)	The study involved an examination of production and drilling operations in Timbalier Bay. Data were reflected in the Bay and offshore to depths of 30 m. Results of this study have been considered inconclusive.
Santa Barbara Channel, California (Mearns & Moore, 1976)	The study involved the examination of two oil platforms located 3.5 km offshore in approximately 30 m depth. At the time of the study, the platforms had been operating for about 15 years. Produced water was not discharged at the platforms.

This summary is largely based on three of the four Gulf of Mexico studies as well as the Santa Barbara study. The Offshore Ecological Investigation is described in the body of the text, but because of the inconclusive nature and controversial history of this project, it is not utilized in this summary. The most comprehensive study of an individual production operation has been for the Buccaneer Field, and data from this study are cited extensively in the summary.

However, it should be noted that the discharge rate of produced water from this platform (~600 bbl/day during the study) was very much less than the average for the EPA 30 platform verification study, both including (9,577 bbl/day) and excluding (4,011 bbl/day) central processing facilities, and is nearer the lower range of discharges (134 bbl/day to 150,000 bbl/day) examined during the EPA 30-platform study. In addition, the Buccaneer Field appears to be in a relatively high energy area where discharges into the water column are rapidly diluted and where sediments which contain contaminants are resuspended and transported away from the area.

5.1.2.1 Hydrocarbons in Water

Volatile liquid hydrocarbons (VLH) were measured in seawater at the Buccaneer Field but were not specifically examined in the Central Gulf of Mexico or Trinity Bay studies. However, one author has reported elevated levels (0.5 ppb) of these compounds in waters of the Louisiana OCS as compared to open ocean water, which suggests that there is a generalized input of these chemicals to the OCS. Sources would include rivers, tanker discharges, and oil/gas seeps, as well as produced water. Aromatic VLHs accounted for 60-80 percent of the total VLH in the surface waters.

Elevated levels of VLH (~65 ppb) were observed immediately below the discharge pipe in the Buccaneer Field, but were rapidly diluted with distance. Reductions of VLH concentrations at the Buccaneer Field platform were on the order of 10^4 to 10^5 within about 50 m of the platform. Concentrations of VLH around the platform were four times higher than at platforms three km away which had no discharge. However, values at this latter platform were still higher than those which were considered anthropogenically affected.

The limited available information suggests that hydrocarbons in the water column are rapidly diluted to low levels, but that these levels persist for considerable distances. The concentrations of hydrocarbons in water will depend on such site specific characteristics as mixing and dispersion and volume of discharge. As already noted, the discharge from the Buccaneer Field is not especially high and the marine environment is characterized by good mixing and dispersion.

5.1.2.2 Hydrocarbons in Sediments

In the Central Gulf of Mexico studies, unresolved complex mixtures of high molecular weight hydrocarbons and the presence of multiple isomers of alkyl aromatic hydrocarbons and parent compounds (e.g., naphthalene and phenanthrene) indicated the presence of petrogenic hydrocarbons at six of the twenty platforms. Only a few sediment samples in areawide studies in the Buccaneer Field contained evidence of petroleum hydrocarbons, based on analyses of high molecular weight alkanes; aromatics were not analyzed.

Elevated levels of naphthalenes (21 ppm) were observed in sediments within 15 m of the outfall in the Trinity Bay study. At 75 m from the platform, the concentrations of naphthalene in the sediments were approximately 9 ppm, or 50 percent of the values observed at the platform. Stations 450 m from the discharge had naphthalene concentrations of approximately 6 ppm. Background levels were approximately 3 ppm (at a distance of 3,963 to 5,793 m). Background levels of naphthalenes in Trinity Bay sediments generally were high, indicating that an areawide elevation in naphthalenes, and possibly other contaminants, may have occurred.

A regression analysis of sediment naphthalene levels indicated that background levels would be achieved at approximately 1,769 m from the outfall. The vertical distribution of sediment naphthalene levels at 15 m from the outfall was examined. Surface levels (0-2 cm) were 21 ppm; a subsurface maximum of 42 ppm occurred at a depth of 6-8 cm. The effluent level of total naphthalenes was 1.6 ppm and dilution was estimated to be 2,000-total at 15 m from the outfall. The ambient water column concentration, therefore, is estimated to be 0.8 ppb, which contrasts to a sediment level of approximately 21 ppm.

The limited data suggest that hydrocarbons (including moderately toxic compounds such as naphthalene) can accumulate in sediments around production platforms. The likelihood of this occurring is greater in shallower and/or low energy areas than in deeper and/or higher energy regions. Because produced water provides a continual source of hydrocarbons, it is possible to have a build-up of moderately toxic compounds which otherwise would tend to be relatively rapidly removed from the system.

5.1.2.3 Hydrocarbons in Organisms

In the Central Gulf of Mexico studies, analyses revealed the presence of low levels of alkylated benzenes, naphthalene, alkylated naphthalenes, phenanthrene, alkylated three-ring aromatics, and pyrene in a variety of fish and epifauna. Isomer distributions of alkylated benzenes and naphthalenes were similar to those seen in crude oil. The investigators concluded that marine organisms in the study area were exposed to a low level of petroleum hydrocarbons from oil and gas development as well as other sources.

Analyses of hydrocarbons in biota in the Buccaneer Field were generally limited to high molecular weight alkanes. These were found in a variety of animals, and there was some suggestion that the feeding habits of some fish could be partially correlated with their content of petroleum hydrocarbons. Fish that are known to feed on the platform fouling community contained higher concentrations of petroleum hydrocarbons than those that feed in the water column.

Results suggest that some accumulation of petroleum hydrocarbons in biota may occur. In the Central Gulf of Mexico study (the only study where lighter aromatics were analyzed in organisms), the presence of benzene and naphthalene compounds suggests that produced water is a possible source of these hydrocarbons.

5.1.2.4 Trace Metals in Sediment and Fauna

Significant increases of trace metals concentrations were observed at stations within 100 m of platforms, for the Central Gulf of Mexico study. Beyond that area, metal levels could usually be explained by natural geochemical processes. Bioaccumulation of metals could not be specifically related to production operations. The Mississippi River probably exerted a dominant influence on trace metal concentrations in sediments and organisms.

Based on a comparison of sediment metal data at the Buccaneer Field with those from other areas of the Gulf of Mexico, accumulations of mercury, manganese, strontium, and zinc were apparent. The sediments around this platform tend to be resuspended and dispersed due to wave and current action, and no significant long-term accumulation occurs. In addition, bioaccumulation of metals in organisms around the platform was limited.

High zinc levels observed in sediments around platforms in the Santa Barbara Channel could have been caused by metal flakes from the platform or metal debris on the seafloor. Rockfish tissues showed increased levels of vanadium.

The results suggest that trace metals accumulate in sediments in the immediate vicinity of production platforms and that there may be bioaccumulation. Sources could include corrosion of metal structures, use of sacrificial electrodes, various activities associated with operations on production platforms, produced water discharges, engine exhaust, and previous drilling discharges.

5.1.2.5 Histopathology Studies

Sites for the Central Gulf of Mexico study where relatively higher incidences of histopathological conditions were observed were generally located in the eastern part of the study area, which was more contaminated with hydrocarbons and trace metals either from production operations or other sources. Because the spadefish had an inherently high incidence of histopathological conditions, its distribution among platforms and control areas (where it is absent) affects the frequency of occurrence of these conditions.

Episodic disease epidemics in spadefish in the Buccaneer Field were attributed to the actions of opportunistic pathogens during periods of natural seasonal stress for the fish. Much of this stress was believed to be due to combinations of natural factors. However, the authors noted there was a possibility that winter disease epidemics may have been related to chronic, low-level discharges of contaminants, because sheepshead residing at the platforms were characterized by a higher degree of histopathological conditions than sheepshead that migrated in and out of the study area. On the other hand, red snapper at the production platforms did not exhibit differences in the frequency of various anomalies as compared to individuals at satellite platforms.

The results from histopathological studies provide little evidence that discharges from production platforms induce histopathological conditions by themselves. The contribution of contaminants by the Mississippi River and the spatial distribution pattern of species are confounding factors.

5.1.2.6 Benthic Studies

During the course of studies conducted as part of the Central Gulf of Mexico program, the area experienced two irregularly occurring phenomena - a tropical storm and anoxic bottom conditions. The investigators noted that these caused so much disruption of the benthic fauna that it was impossible to clearly describe populations or discern the effects of platform discharges.

Benthic assemblages around the production platform in the Buccaneer Field were different from most of those in the study area. Stations near the platform (< 100 m) had reduced faunal abundance, relatively high species turnover, and the presence of certain species that were rare in the remainder of the study area. It appears that toxic effects, perhaps associated with the presence of toxic chemicals (hydrocarbons and/or biocides), appeared to contribute in part to these alterations.

Similar benthic impacts were observed in the Trinity Bay study. Within ~15 m of the discharge, the sediments were almost devoid of benthic infauna. Numbers of individuals and species increased with distance from the platform. (The investigators considered stations more than 450 m from the platform to be unaffected because organism densities exceeded a number thought to be representative of control areas.) The low abundance of benthic organisms was correlated with the elevated concentrations of total naphthalenes in the sediments.

The results of these studies, in particular Buccaneer Field and Trinity Bay which occurred in water depths of 20 and 2.5 m, respectively, suggest that production platforms can have an adverse effect on local benthic infaunal populations. Factors that may affect the degree to which produced water discharges affect the benthos include water depth, volume of discharge, local dispersion characteristics, presence of suspended sediments, and physical characteristics of the seafloor.

5.1.3 Catch and Effort Statistics

Trends in catch statistics for commercial fish landings were examined for the Gulf of Mexico to determine if there are any indications that offshore oil and gas operations could be a factor affecting commercial fish and shellfish yields. It is recognized that other factors such as adequate reporting, overfishing, natural perturbations, fresh water inflow, and other sources of pollution could all be factors affecting catch statistics. However, the statistics do permit some gross comparisons to be made.

Landings data for several important commercial fish and shellfish - shrimp, red snapper, and blue crab - indicated consistently lower catch-per-unit-effort from Louisiana waters as compared to the rest of the Gulf of Mexico. Inasmuch as over 88 percent of the offshore structures in the Gulf are located in Louisiana, this raises an environmental concern with respect to discharges from oil and gas platforms.

5.2 INTRODUCTION TO FIELD STUDIES

A number of field studies have been conducted to characterize material behavior and pollutant concentration, and to monitor potential environmental effects of discharges from offshore oil and gas operations. These field studies complement the laboratory studies discussed in Section 4, and give a real-world perspective to the transport processes identified in Section 3. This section focuses on the environmental effects documented in the available literature from the offshore drilling areas of the United States. Information on areas of special interest, Flower Gardens, Georges Bank, and Norton Sound, and administrative activities for these areas is presented in Appendix A.

Major studies addressing exploratory drilling operations have been conducted in the Mid-Atlantic OCS off the New Jersey coast (EG & G, 1982), Georges Bank off the Massachusetts coast (Payne et al., 1982; Bothner et al., 1982; Blake et al., 1983), Lower Cook Inlet, Alaska (Lees and Houghton, 1980), the Beaufort Sea (Crippen et al., 1980), and Tanner Bank off the southern California coast (Ecomar, 1978; Meek and Ray, 1980; Ray and Meek, 1980). Baker et al. (1981), in their investigations in Louisiana OCS, found evidence of sublethal chronic effects within 500 m of a petroleum production platform due to hydrocarbons and trace metals, some of which appeared to be derived from drilling fluids. Ayers et al. (1980b) conducted a study of plume dispersion in the Gulf of Mexico, but this project did not address the impacts to indigenous marine biota.

The major studies analyzing environmental impacts from produced water discharges have been conducted in the Gulf of Mexico. Two of the most detailed field investigations are the "Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, 1975-1980" (Middleditch, 1984) and the "Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexico" (Bedinger et al., 1981). Some of the parameters examined by these studies were previously scrutinized during the Offshore Ecology Investigation which focused on Timbalier Bay, Louisiana (Bender et al., 1979). The most significant effects of produced waters on biological communities have been documented when the discharge is into shallow bays and estuaries. API sponsored a study of the environmental effects of produced water discharges into Trinity Bay, Texas (Armstrong et al., 1977).

The summary for this section contains a synthesis of the major studies as well as conclusions drawn from these studies. The remainder of this section provides a synopsis of these studies. It is organized into two major categories: discharge of drilling fluids and production operations. Drilling-related studies are limited to exploratory drilling. There have been no comprehensive effects studies related to development drilling.

5.3 DISCHARGES OF DRILLING FLUIDS AND CUTTINGS

5.3.1 Mid-Atlantic Outer Continental Shelf

An extensive study of a mid-Atlantic OCS well (EG & G, 1982) was funded by the Offshore Operators Committee and Exxon at the request of EPA Region II. The overall objective of the program was to evaluate the effects of drilling discharges on ambient water quality, bottom sediments, and the benthic community around an exploratory well. The study area was located in Baltimore Canyon, which is approximately 156 km (97 miles) off the coast of New Jersey. This is a low energy area with an average depth of 120 meters. Drilling of the exploratory well took place from January 4, 1979 to July 15, 1979.

The program consisted of four separate study elements: (1) a pre-drilling survey to examine the physical, chemical, and biological conditions in a 3.2-km diameter area around the well site; (2) a discharge monitoring study to provide quantity, composition, and fate information concerning the muds and the solids control equipment (SCE) discharges; (3) a first post-drilling survey performed two weeks after the completion of the drilling activity examining the same parameters as the pre-drilling survey in a 6.4-km diameter area around the well; and (4) a second post-drilling survey conducted one year later in the same 6.4-km diameter area.

During the drilling period, a total of 30,800 barrels of bulk muds and 6,400 barrels of SCE discards were discharged into the ocean. The upper plume formed from the discharges contributed significantly to the suspended solids concentration of the water column in the immediate vicinity of the well, affecting light transmissivity. The suspended solids in the upper plume dropped by a factor of 10^4 within 100 meters of the discharge point and approached background levels within 350-600 meters.

Physical/chemical alterations to the surface sediments near the well site were detectable up to two years after cessation of discharge due to the low energy nature of the benthic environment. These alterations included the presence of drill cuttings (visible accumulations within 100 m of discharge), mineralogical changes, and elevated barium concentrations in the sediments. Normal sediments in the vicinity of the well were comprised mostly of sand, silt, clay, and gravel. Discharges of drilling wastes led to localized alterations of the bottom materials. Increased clay content of the surface sediments for a distance of 800 m in a southwesterly direction was detectable immediately after drilling was terminated but not one year later. Barium levels in the sediments were also elevated near the discharge in samples taken during post-drilling surveys. Sediment barium concentrations were greatest within the immediate vicinity of the well and decreased exponentially with distance. There were significant changes in the leachable fractions of barium, nickel, lead, vanadium, and zinc in the top 15 cm of the sediments. No elevated levels of oil and grease were observed.

During the course of this study, it was assumed that one-mile and/or two-mile stations would be beyond the influence of the discharges. However, all one-mile stations sampled in both past drilling surveys had elevated sediment barium levels and showed increased barium concentrations in polychaetes and brittle star tissues. One of four two-mile stations also had increased barium concentration in the sediments following drilling. No sediment concentrations were available for this station (or any two-mile station) prior to drilling discharges, so it is not possible to ascertain whether this elevation was due to drilling discharges or natural or historical phenomena. No tissue data were available for trace metals in organisms at any two-mile station either pre- or post-drilling. Due to these data gaps one cannot be certain that discharge influences did not extend out to the two-mile (3.2 km) stations.

Benthic organisms including molluscs, polychaetes, and brittle stars were collected during both post-drilling surveys for tissue analysis and held for a 24-hour depuration period prior to analysis. This period is less than the conventional 48- to 72-hour period. Tissues were examined for arsenic, barium, copper, chromium, lead, mercury, nickel, vanadium, and zinc. Only barium and chromium levels in tissues showed an increase over background levels. Increased concentrations of barium in tissues were detected in the first post-drilling survey, but had decreased to pre-drilling levels after one year. Chromium concentrations were elevated during the second post-drilling survey. There was no correlation between either barium or chromium concentrations in tissues and concentrations in the sediments.

The abundance of fish and decapods (mobile megabenthos) increased in the vicinity of the well. These organisms were probably attracted to the area as a result of the increased microrelief of the cuttings piles and food availability. Sessile megabenthos were subject to the effects of burial. Densities of the major taxa decreased between the pre-drilling and the first post-drilling surveys. The densities showed signs of a partial recovery after a one-year period (pre-drilling = 8,011 ind./m^2; post-drilling I = 1,729 ind./m^2; post-drilling II = 2,638 ind./m^2). Possible impacts of drilling discharges include burial, diminished larval recruitment, and increased predator pressure. There was a significant negative correlation between sediment barium concentrations and the abundance of brittle stars following drilling. The lowered abundance of brittle stars was still evident during the second post-drilling survey.

EG & G (1982) reported that reductions in abundances may be due to natural variability instead of drilling discharges since they occur at the one- and two-mile stations. Unfortunately, there are no pre-drilling abundance data available at the two-mile stations. Without this background data, it is not possible to determine whether or not the one- and two-mile stations are beyond the zone of influence.

There was little change in the gross taxonomic structure of the benthic community. Species richness paralleled decreases in abundance, dropping from a mean areal richness of 70 species/0.2 m^2 to 38 species/0.2 m^2. There was little change in the Shannon diversity or Pielou evenness indices. For these analyses of community structure (diversity and evenness), the benthic data set was reduced as follows:

- "Singleton" species (taxa represented by a single individual) were eliminated from the data set;
- taxa were eliminated if they were represented by lower-order taxa and accounted for less than 20 percent of the total individuals in the group; and
- when a higher order taxon contained 20 percent or more of the total number of individuals in that group, all lower-order taxa were merged with the higher taxon.

The reason given for this reduction in the data set was to allow greater confidence in the validity of the taxonomic categories used in the structural analysis. However, these reductions may mask important changes such as the elimination of a sensitive species and/or a reduction in the total number of species. This may bias the results of the diversity index, since the most important component of Shannon's equation is the evenness factor (number of individuals in species i). Accordingly, it seemed appropriate to recompute the Shannon-Weaver index on the unreduced data set. The results of this test, however, failed to indicate any major changes in community structure.

5.3.2 Georges Bank

The Georges Bank Monitoring Program was implemented by the Minerals Management Service in cooperation with EPA, other Federal agencies, and the affected coastal states in July 1981 to determine the potential impact of exploratory drilling activities on benthic communities from Lease Sale No. 42 at Georges Bank, off Massachusetts. One major goal of this program has been to identify and document immediate and long-term changes in hydrocarbons and trace metals in sediments and epifauna as they relate to drilling activities and proximity to exploratory platforms.

Georges Bank is located approximately 300 km (180 miles) southeast of Cape Cod, Massachusetts. The monitoring program consists of a series of seasonal cruises. The first four cruises took place in July 1981, November 1981, February 1982, and May 1982. These cruises spanned the period during which the eight exploratory wells were drilled (December 1981 to June 1982). Cruises have since continued on a quarterly schedule.

Bothner et al. (1982) analyzed trace metals in the bottom sediments. Their objectives were to determine whether discharged drilling fluids accumulated on Georges Bank and the extent to which trace metals increased in the sediments as a result of accumulating muds. The sediments of Georges Bank are typically 95 percent sand except for an area located south of Nantucket Island. This area, appropriately referred to as the

"Mud Patch," is thought to be a major depositional site and contained from 38 to 97 percent fine materials (less than 62 µm in diameter). Pre-drilling samples had metals concentrations lower than crustal rocks, suggesting the area is essentially uncontaminated with respect to the heavy metals analyzed (aluminum, barium, cadmium, chromium, copper, iron, lead, mercury, manganese, nickel, vanadium, and zinc). Barium increases in the sediments were noted following the initiation of drilling activities. The distribution of barium in the sediments appeared to be biased to the west, which is consistent with the expected transport based on mean current flow. Block 410 in the lease area showed an average barium increase from 30 to 107 ppm within a 200 m zone and a smaller increase at distances up to 2,000 m. Block 312 showed average barium increases from 37 to 67 ppm. Smaller increases were measured at distances of up to six km from the drilling site. There were no drilling-related changes in the concentrations of chromium or other metals in the bulk sediments. Increases in aluminum, chromium, copper, and mercury in the fine fractions of the sediments were observed at the drill site in Block 410.

Payne et al. (1982) analyzed sediments for hydrocarbons and epifaunal tissues for hydrocarbons and trace metals. Overall, the aromatic hydrocarbon levels in the sediments were extremely low and essentially constant over time. The highest and most variable aliphatic and aromatic hydrocarbons were observed in the "Mud Patch." Sediment analyses indicated that the majority of the aliphatics were of biogenic origin and that drilling fluid components accumulated in the "Mud Patch." There was also little evidence of hydrocarbons accumulating in tissues. One sample (*Arctica islandica*) had elevated concentrations, compared to samples taken at other locations, of polynuclear aromatic hydrocarbons common to drilling fluids which may have been present. However, it is not possible to categorically state whether drilling fluids were the source of the hydrocarbon accumulation. There was no evidence of metals levels in epifaunal tissues changing over time. The total number of tissue samples was limited, so a complete analysis was not possible. Levels of cadmium, chromium, copper, iron, lead, nickel, and zinc showed no significant change between the 1977 (ERCO) and 1982 (Payne et al., 1982) sampling episodes.

The sampling plan for Georges Bank had two components. The long-term or regional stations were established as three transects: one through the lease tract area, one upcurrent (eastward), and one downcurrent (net flow) (Figure 5-1). Additional stations were established at the center of the Bank and at depositional sites in the "Mud Patch" south at Nantucket, in Lydonia and Oceanographic Canyons, and in the Gulf of Maine on the north side of the Bank. A site-specific set of 29 stations was sampled at 80 m depth in Block 312 near the center of the lease site area (Figure 5-2). Stations were established in a radial pattern at distances from 100 m to six km as well as at the rig site itself. A second small rig-site study was conducted at Block 410 in 140 m on the southern flank of the Bank. Three stations were located within 200 m of the rig site and others approximately two km upcurrent and downcurrent.

The long-term stations situated around the Bank were established to examine trends over a large area and a long period of time. Since only eight wells were drilled in a one-year period, no drilling-related changes could be detected in

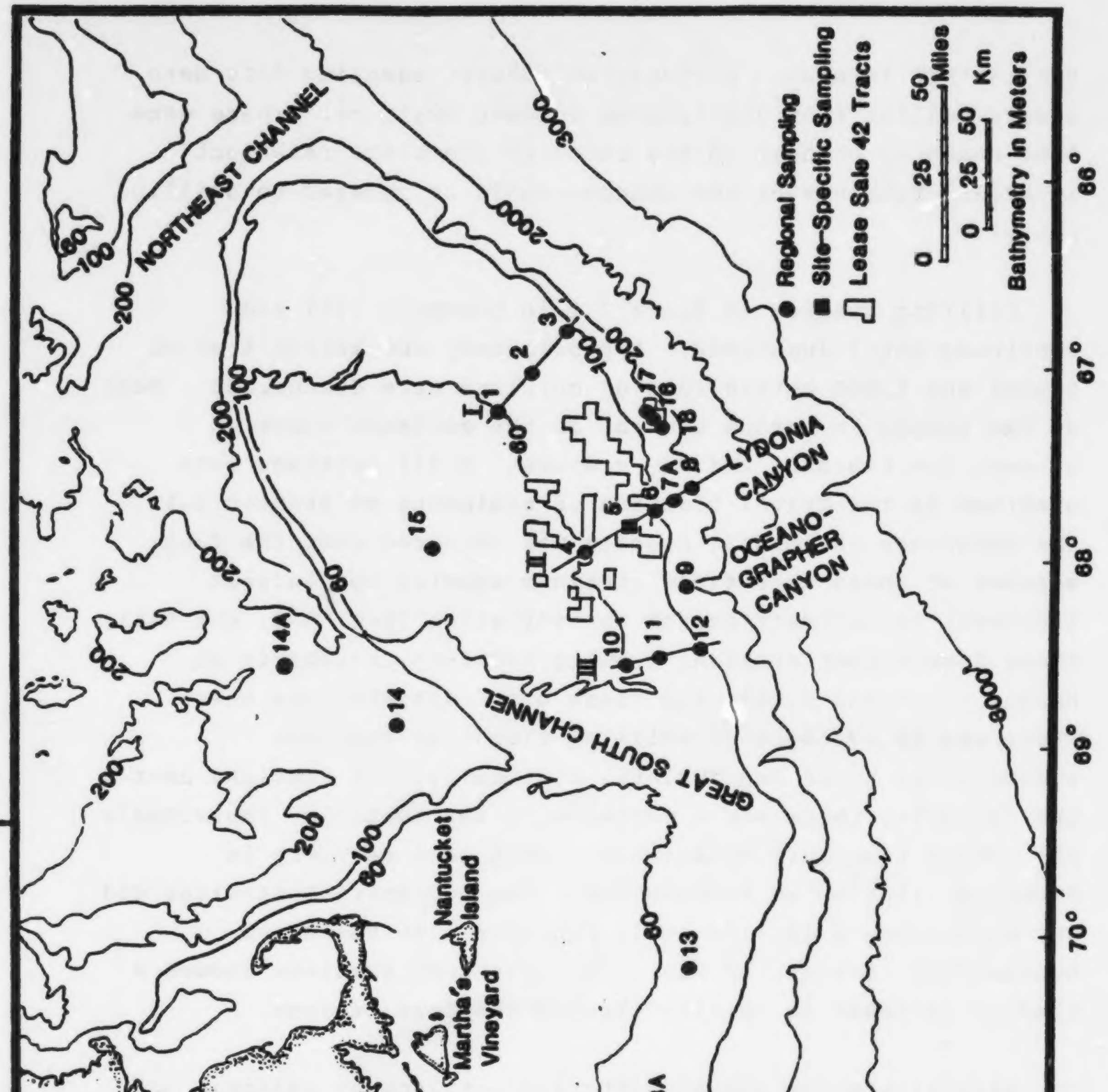


FIGURE 5-1 LONG-TERM REGIONAL STATIONS
(from Blake et. al., 1983)

the benthic infauna. Differences between sampling data were always smaller than differences between stations. There were some seasonal changes in the fauna at Block 410 (stations 10,17,18) but none of the changes could be related to drilling activity.

Drilling started in Block 312 in December 1981 and continued until June 1982. Approximately 900 metric tons of fluids and 1,000 metric tons of cuttings were discharged. Most of the change in barium content at the sediment occurred between the February and May cruises. Drill cuttings were observed in the gravel fraction of sediments at Station 5-1. The abundance of several species was compared over the four seasons at those near-field stations showing the largest increment in sediment barium concentration (5-8, 5-2, and 5-1); those downcurrent stations showing moderate increments in barium (5-10 and 5-25); and those upcurrent stations where there was no evidence of drilling fluids at cuttings accumulation (5-28 and Regional Station 2). At stations near the rig site, there was a decrease in the number of individuals per sample from July to November, with good recovery in February, continuing through May. The downcurrent stations did not experience a decline until February, and there was substantial recovery by May. The upcurrent stations showed a gradual increase in density through the four seasons.

Several species showed differing patterns of seasonal abundance. The most dramatic population decline was shown by the amphipod _Ericthonius_ _rubricornis_, an epifaunal suspension feeder.

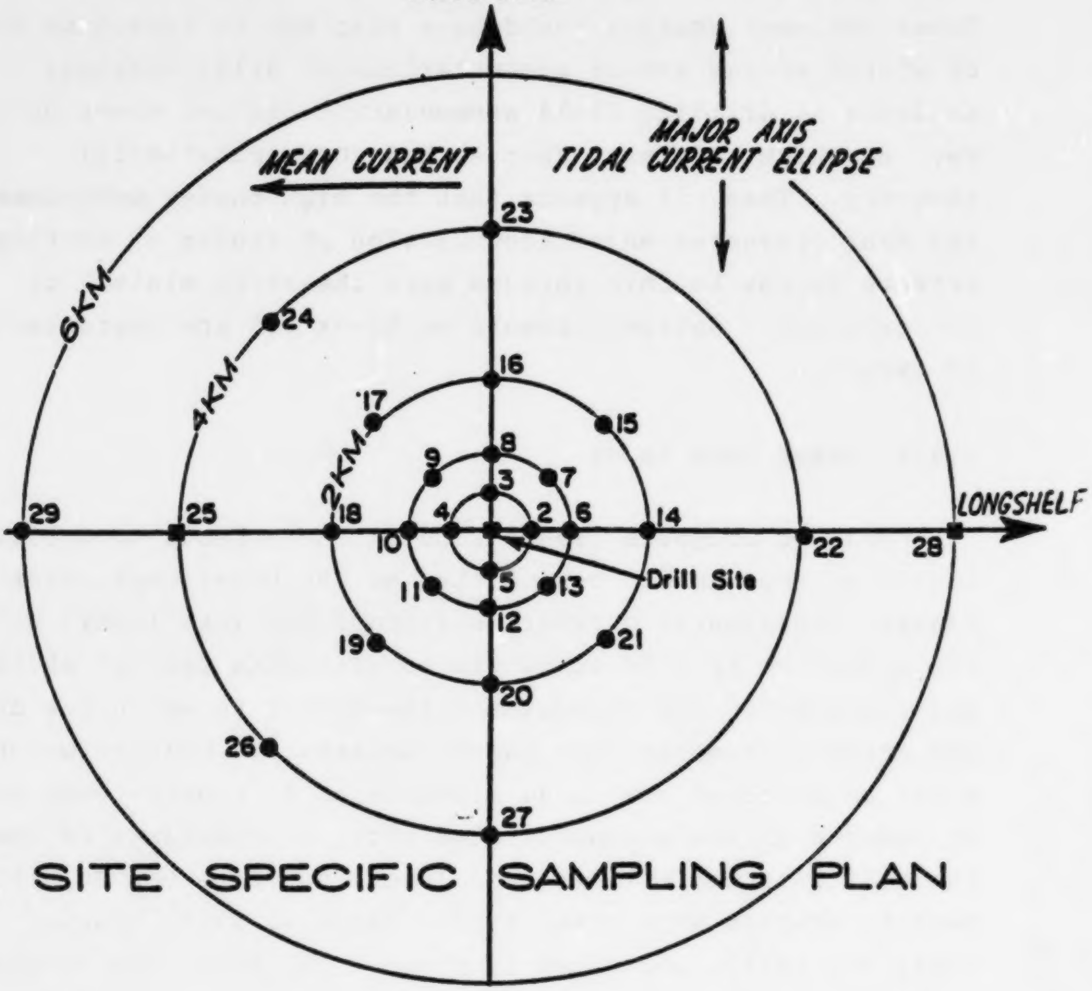


FIGURE 5-2 Site-specific sampling array around regional station 5. Stations 5-7, 5-13, 5-17, 5-21, 5-23, 5-24, 5-26, and 5-27 are secondary stations (of lower priority) and are presently archived.

(from Blake et. al., 1983)

Most of the changes observed near the rig site can be correlated with changes in sediment grain size characteristics. These sediment changes could have been due to secondary action of winter storms and/or accumulations of drill cuttings. Evidence of drilling fluid accumulation did not occur until May, by which time most species had shown substantial recovery. Thus, it appears that the high energy environment of the Bank prevented major accumulation of fluids or cuttings and effects on the benthic infauna were therefore minimal or non-existent. Bottom currents at Block 312 are approximately 50 cm/sec.

5.3.3 Lower Cook Inlet

Lees and Houghton (1980) studied the effects of drilling fluids on the benthic communities at the Lower Cook Inlet, Alaska, Continental Offshore Stratigraphic Test (COST) well. The objective of this study was to determine species abundance and composition and to evaluate the extent to which the drilling activities may change these parameters. Changes which might be detected are large alterations in species composition or changes in the richness, diversity, or abundance of species. The COST well was drilled from June 7 to September 26, 1977. Benthic samples were taken before (June 6, 1977), during (July 25, 1977), and after (September 19, 1977) the completion of drilling, using a Ponar dredge. Underwater television pictures of the seafloor showed no visible accumulation of cuttings. The maximum accumulation of cuttings in any benthic sample was three percent by weight. Barium concentrations in the benthic samples were within pre-drilling ranges.

Benthic surveys showed a population typical of a shallow, high energy, sandy substrate in a northern subarctic region. There were some changes in benthic community composition over the duration of the study, but none of the changes were significant and none could be attributed to drilling discharges. Individual and species abundances and Brillouin diversity did not change significantly within 200 m of the well site. Lees and Houghton did note that a comparison of pre- and post-drilling data was complicated by an incomplete knowledge of seasonal cycles for the arctic species and sampling anomalies (i.e., inability to use same control sites for pre- and post-drilling samples).

It was concluded that, due to the high energy nature of the environment, drilling fluids and cuttings did not accumulate on the seafloor at rates sufficient to alter the benthic communities.

5.3.4 Beaufort Sea

Crippen et al. (1980), under the sponsorship of ESSO Petroleum Resources, Inc., examined metal levels in sediments and benthos resulting from drilling fluid discharges into the Beaufort Sea, Alaska. The primary objective of the program was to investigate the environmental significance of metals in drilling fluids discharged to the aquatic environment. The study site was an artificial island constructed from local borrow material in the Beaufort Sea near the Mackenzie River delta. The average depth of the study area was approximately seven meters.

The exploratory well under study was drilled from November 8, 1975, to May 19, 1976, and the sampling program was carried out during August of 1977. The investigators sampled 47 stations for arsenic, cadmium, chromium, lead, mercury, and zinc in the sediments and infaunal tissues. The barite used in the drilling fluid which was discharged was a "dirty barite," and contaminated with these same metals. Mercury concentrations in the drilling fluid were 185 times higher than background levels in the sediments.

When compared to background concentrations, elevated levels of arsenic, cadmium, chromium, lead, and zinc in the sediments were found at one or more stations near the discharge site. Mercury levels were clearly elevated within a distance of 100 m. No correlation was found between metals levels in the sediments and metals levels in tissues. There was some evidence of bioaccumulation of mercury (up to an order of magnitude) at two stations; other than this, evidence of bioaccumulation of metals in infaunal tissues was absent. Density and biomass of benthic organisms was reduced within 300 m of the artificial island. Crippen et al. (1980) concluded that smothering and modification of the substrate by borrow material during construction of the island had a greater effect on benthic populations than drilling fluid disposal.

5.3.5 Tanner Bank

Tanner Bank is located approximately 160 km offshore from Los Angeles, California. The area has been designated a "unique biological area" by the Pacific Office of the Bureau of Land Management for many reasons. The abundance and health of this unusual assemblage of organisms is exceptional. Baseline studies funded by the BLM (Smith, 1976) have identified 94 completely new species. One discovery was of Neopilina sp., an extremely rare monoplacophoran mollusc thought to have long been extinct.

Ecomar (as in Thomas et al., 1983; Meek and Ray, 1980; Ray and Meek, 1980) carried out a water quality investigation of the area in conjunction with the drilling of an exploratory well by the Shell Oil Company. Sampling during discharges of drilling fluids (January to March, 1977) showed that the discharges caused minor and transient modifications to the receiving waters. The bulk of the discharged materials settled to the bottom within 120 m of the discharge, while background trace metal and suspended solids concentrations were reached within 200 m. Ecomar (reported in Thomas et al., 1983) reported that "mud and cuttings dilution and dispersion was so complete that residual materials were visually undetectable on the rock reef or directly below the discharge site." An investigation of the reef-associated biota covering six linear km from the discharge site concluded that drilling operations at Tanner Bank had no significant observable adverse effect on the associated reef community.

5.4 DISCHARGES OF PRODUCED WATER

5.4.1 Buccaneer Gas and Oil Field

The environmental assessment of the Buccaneer Gas and Oil Field involved a five-year field and laboratory research project funded by EPA through an interagency agreement with NOAA. The Buccaneer Field study was initiated in 1975 and completed in 1980.

The study examined the effects of chronic, low-level exposure of the ecosystem to contaminants generated by oil and gas production activities. Specifically, the objectives of the project were (1) to identify and document the types and extent of biological, chemical, and physical alteration to the marine ecosystem, (2) to identify the specific pollutants, their quantities and effects, and (3) to develop the capability to describe and predict fate and effects of environmental contaminants.

The Buccaneer Field is located approximately 49.6 km southeast of Galveston, Texas, in 20 m water depth. There were 17 structures in the Field including two production platforms, two living-quarters platforms, and 13 satellite structures. The discharge of produced water was estimated at 600 bbl/day, which is not a particularly high discharge. The area could be characterized as a relatively high energy environment. The work progressed in five stages:

- Brief pilot study in the autumn and winter of 1975-1976
- Extensive biological/chemical/physical survey in 1976-1977 comparing Buccaneer Field to adjacent control areas
- Investigations within the Buccaneer Field (1977-1978) comparing conditions around production platforms which discharge produced water to those around satellite structures which have no such discharges
- Studies in 1978-1979 focusing on a) the concentration and effects of pollutants in major components of the marine ecosystem, b) the effect of circulation dynamics and hydrography on the distribution of pollutants, and c) mathematical models to describe and predict sources, fate, and effects of pollutants

- Further focus on elements (a) and (b) above during 1979-1980 and the preparation of milestone reports.

Brooks et al. (1980) measured the concentrations of volatile liquid hydrocarbons (VLH) in seawater at the Buccaneer Field. Elevated levels (~65 ppb) were observed immediately below the discharge pipe, but were rapidly diluted with distance. Menzie (1982) estimated that reductions of VLH concentrations at the Buccaneer Field platform were on the order of 10^4 to 10^5 within about 50 m of the platform. Concentrations of VLH around the platform were four times higher than at platforms three km away which had no discharge. However, values at this latter platform were still higher than those Sauer (1980) considers anthropogenically affected.

Brooks et al. (1980) concluded that production platform discharges in the Buccaneer Field do not measurably alter the bulk composition of suspended particulates or biological activity (as measured by the biochemical indicators chlorophyl and ATP) in the water column in their immediate vicinity. Surficial sediment data indicated that there was considerable movement of fine grain material in the area, so contaminants introduced to the sediments in Buccaneer Field may be rapidly removed from the platform vicinity by resuspension and transport. Only contaminants associated with coarse-grained material would be expected to remain in the Field. These observations were confirmed by the seasonal contamination patterns of trace metals and hydrocarbons in the Field.

Gallaway (1980) selected the following indicators for the study of biological impacts:

- standing crop biomass, community structure and composition, production and health or condition of the biofouling community
- relative abundance of demersal fishes and macrocrustaceans
- pelagic and reef fishes

He observed that there was a rich and diverse biofouling community associated with the production platforms. These artificial reefs aggregated nektonic species preferring these habitats, as well as their predators. Produced waters were toxic but the measurable effects on biota were generally restricted to within a few meters of the outfall, as evidenced by effects on the biofouling community. The biomass levels and production rates of the biofouling community were depressed in the vicinity of the outfall (generally to a vertical distance of one meter and a horizontal distance of ten meters).

Middleditch (1980) examined 31 fish species for petroleum hydrocarbon contamination, 15 of which contained measurable quantities of petroleum hydrocarbons (alkanes, at 1.1-6.8 ppm). Tissue samples were not analyzed for lighter aromatic hydrocarbons. A degree of correlation was found between the feeding habits of some fish and their hydrocarbon content. Those fish which fed on the biofouling community, which contained elevated hydrocarbons, had higher concentrations than those which fed in the water column. Hydrocarbon concentrations were usually higher in the liver than in other tissues. Additional detail on this part of the study is provided in Section 3.

The major pool of contaminants in the Buccaneer Field is the surficial sediments (Middleditch, 1980). He determined that the sediments contained concentrations of petroleum alkanes as high as 50 ppm. Moreover, these concentrations were dependent upon the total quantity of contaminants discharged from the platform in the produced water. Middleditch's analysis was limited primarily to alkanes.

Petroleum hydrocarbons were detected at the air/sea interface and in the mixing zone below the discharge pipes, but were rarely found in above ambient concentrations in other seawater samples (Middleditch, 1980). Based on data presented by Brooks et al. (1980), concentrations of volatile liquid hydrocarbons (VLH) at the production platform were approximately four times higher than at a platform three km away which had no discharge. Yet, values at this latter platform were still higher than those given by Sauer (1980) for anthropogenically influenced water. Tillery (1980) showed that brine discharges have concentrations of barium, cadmium, chromium, iron, mercury, manganese, thallium, and zinc significantly higher than seawater. However, there has been a good deal of uncertainty about the quality of the data on metal concentrations in brines.

The currents and waves tend to dilute and disperse brine discharges immediately upon discharge. There have been short-term accumulations of barium, cadmium, chromium, copper, and lead in the sediments, and more persistent accumulations of mercury, manganese, strontium and zinc. There is no evidence of bioaccumulation of trace metals in either the biofouling community, spadefish, or sheepshead. Indications of accumulation in the longspine porgy and sugar shrimp which were observed cannot be confirmed statistically.

Barium levels in the gill tissues of diseased fish were much higher than in healthy fish gills. Those higher barium concentrations could be caused by bioaccumulation or be associated with fine particles trapped in the gills, either of which may be responsible for the disease.

Alterations in the benthic fauna around the Buccaneer production platform were observed by Harper et al. (1980). Stations within 100 m of the platform had depressed faunal abundance, a relatively high species turnover rate, and the occurrence of a few species that were more frequently found at these stations than in the remainder of the study area. The authors offered several possible explanations for the altered benthic conditions. However, it appeared that toxic effects, perhaps associated with the presence of hydrocarbons and/or biocides, were contributing at least in part to the altered benthic community composition and abundance.

5.4.2 Central Gulf of Mexico

The ecological investigation of petroleum production platforms in the Central Gulf of Mexico (Bedinger et al., 1981) was carried out by the Southwest Research Institute under the sponsorship of the Bureau of Land Management as part of their OCS Environmental Studies Program. The study area for this investigation included 20 petroleum production platforms and four control sites in the Louisiana OCS. The study was aimed at defining the long-term cumulative effects of petroleum production in this region. However, the Mississippi River discharge exerted a major influence over the study area, and this made it difficult if not impossible to discern effects attributed solely to production operations.

The specific objectives of this study were:

- Determination of the distribution and concentration of petroleum hydrocarbons, selected trace metals, and well drilling related substances in surficial sediments and tissues of commercially and/or ecologically important benthic and demersal species.
- Examination of microbial hydrocarbon degradation and nutrient cycling processes and related nutrient chemistry in surficial sediments.
- Comparison of benthic communities in the immediate vicinity of platforms with those at control sites.
- Examination of the distribution of petroleum hydrocarbons, selected trace metals, and well drilling related substances in sediments according to depth.
- Investigations of biofouling communities and the "artificial reef" effect at a variety of platforms.

The program was designed to sample at various distances from the platforms in order to determine long-term buildup of contaminants in the sediments and foodweb. Sampling took place during 1978 and 1979 at stations located 100, 500, 1,000, and 2,000 m from the platforms.

Nulton et al. (1981) analyzed for low molecular weight hydrocarbons (LMW-HC) in the water column, total organic carbon in the sediments, and high molecular weight hydrocarbons

(HMW-HC) in the sediments and organisms. The LMW-HC analyses of seawater indicate the entire area has a baseline level of C_1 - C_4 saturated hydrocarbons above that of the open ocean. Three sites had LMW-HC concentrations considerably above the baseline, which were presumably due primarily to petroleum production-related activities as well as venting of gas. Sediments showed a trend of greater contamination in eastern and near-shore areas, which are the areas of greatest production. Tissue analyses showed low-level accumulations of benzenes, naphthalenes, phenanthrene, and pyrene in fish and macroepifauna. Isomer distributions of alkylated benzenes and naphthalenes were similar to those in crude oil. Nulton et al. concluded that the biota were evidently subjected to chronic exposure to low levels of petroleum hydrocarbons derived from oil and gas production as well as other sources such as combustion products from atmospheric emissions.

Marine organisms were analyzed for tissue levels of cadmium, chromium, copper, iron, nickel, lead, zinc, barium, and vanadium. However, the project was not sufficient in scope to provide an adequate number of individual organisms to allow statistically significant tissue results; therefore, the data for metals in organisms are of limited value (Tillery, 1980). Trace metal impacts from the Mississippi River probably exert a dominant influence in the area, which masks the effects of the platforms (Tillery et al., 1981).

An analysis of the histopathology of invertebrates and fish in the area (Sis et al., 1981) showed that the sites that ranked high in the number of histopathological conditions were located in the eastern part of the study area. The platforms which consistently showed the highest trace metals and hydrocarbon contamination were the locations where histopathological conditions in fish were common. Because the spadefish had a high incidence of histopathological conditions, its distribution among platforms (where it was common) and control areas (where it was not common), affects the frequency of occurrence of these conditions.

The results of the artificial reef studies (Gallaway et al., 1981) indicate that the production platforms have apparently expanded the available habitat for numerous fish and invertebrate species. The produced water discharges had localized detrimental effects on the fouling biota such as lowered biomass and density, low survival rates of barnacles, low production and recolonization rates, and a greatly altered community structure.

Because of anoxic conditions and storm events, the benthic community was greatly disturbed during the study period. Therefore, it was not possible to examine the effects of production operations on these organisms.

5.4.3 Timbalier Bay

The Gulf Universities Research Consortium conducted the Offshore Ecology Investigation (OEI) of Timbalier Bay to help determine the ecological impact of petroleum drilling and production in coastal Louisiana. Morgan et al. (1974) summarized eight synoptic field sampling and data collection exercises in Timbalier Bay and offshore to a depth of 30 m (100 ft) covering a period from 1972 to 1974. The study encompassed the work of 23 principal investigators. An OEI Council of four scientists evaluated and interpreted the results of the 23 individual investigations.

Studies examined the physical setting (i.e., water mass movement, currents, geology), the chemical setting (i.e., inorganic nutrients, hydrocarbons, trace elements), and the biology (i.e., phytoplankton, primary productivity, benthic plants, zooplankton, benthos, and ichthyofauna) of the area. The final consensus report of the first OEI Council (Morgan et al., 1974) stated that "No harmful impact on the environment from production or drilling is demonstrated" by the data collected. They concluded that 79 percent of the individual studies demonstrated either no impact or a beneficial impact, while the remaining 21 percent of the investigations were inconclusive for one reason or another. Their general conclusions concerning the area were:

- Natural phenomena have a much greater impact on the ecosystem than petroleum activities.

- Concentrations of compounds of OEI interest are sufficiently low to present no known biological hazards.

- Every indication of good ecological health is present.

- Timbalier Bay has not undergone significant ecological change attributable to petroleum activities.

In 1979, Bender et al. undertook a reexamination of the data and conclusions drawn from the OEI, in which they were critical of the original OEI study design as a means of responding to the program's objectives. Based on the original data collected, which showed evidence of petroleum contamination in the sediments at control and experimental areas, Bender et al. (1979) surmised that "most of the OEI data appear to be collected from the same 'population' and should be expected to be the same within statistical errors of sampling." In addition, the temporal and spatial variability of species and the "complete" mixing of the Gulf hydrocarbon content suggest that the classical experimental versus control design may be inappropriate. Bender et al. also noted that the limited data-gathering effort of the OEI was probably inadequate to definitively detect the low-level effects of oil contamination.

The above qualifications notwithstanding, Perry (1974, reported in Bender et al., 1979) found the production sites to have the lowest fish biomass and species diversity, and attributed this to encrusting of the bottom by drilling muds. Other investigators produced data which indicated elevated cadmium, lead, and zinc levels in the immediate vicinity of the well. Overall, however, the results of the OEI are inconclusive. These findings do not clearly indicate the effect or the lack of an effect from oil drilling and production in the Gulf of Mexico.

The re-evaluation also led to the conclusion that there was no indication of environmental stress resulting from oil-related activities. However, this conclusion was tempered with a few qualifications regarding the limitations of the original experimental design and data base for defining the chronic effects of oil. The researchers concluded that ". . .the natural variability inherent in the biological, physical, and chemical processes in the Gulf of Mexico precludes acquisition of adequate, representative, or valid baseline data in a period limited to two years."

5.4.4 Trinity Bay

Trinity Bay, Texas, is a shallow, turbid bay in the northeastern arm of the Galveston Bay complex. It contains several oil fields and is an important area to recreational and commercial fishermen. The separator platform chosen as the target for this study is the largest in the Fishermen's Reef Field. The oil and brine mixture is pumped from the ground into separator tanks where it is allowed to separate. The oil is transported to shore through pipelines and the brine is discharged to the bay through a shunt whose mouth is three feet (1 m) above the bottom. The mean depth at the platform is eight feet (2.5 m) and the sediments are predominantly silty clay.

The study sought to determine the concentrations of naphthalenes in the sediments and the abundance and distribution of benthic organisms in relation to distance from the platform, and whether these were correlated. Further, the researchers compared concentrations of specific hydrocarbons in effluents, bay water near the platform, and sediments, and determined whether there was a zone of stimulation around the platform.

Naphthalenes were chosen to indicate the presence of petroleum hydrocarbons in the water and sediment because they are nonbiogenic in origin and are known to be some of the most toxic components of petroleum.

The highest levels of naphthalene in the sediments (up to 110 ppm) were found within 15 m (50 ft) of the platform outfall. Although the effluent was quickly diluted (2,000-fold within 15 m), naphthalenes accumulated in the sediments to concentrations 13 times the effluent concentrations. The high and persistent naphthalene levels in the sediments were probably due to turbid conditions and the slow degradation rate of oil in sediments. Naphthalene concentrations decreased as the distance from the outfall increased.

There was a significant inverse correlation between sediment naphthalene concentrations and the number of benthic organisms. The bottom was essentially devoid of benthos within 15 m of the platform and the number of benthic species and individuals was severely depressed for a radius of 152 m (500 feet). Apparently a low persistent concentration of naphthalenes was capable of restricting many species of benthic organisms. The number of species increased with distance from the platform. These results parallel those of an earlier investigation (Mackin, 1971) in a shallow (2.4 m) Texas estuary. Mackin reported that produced water discharges totally eliminated the benthic community within 15 m of the discharge and that some mortality of the benthos was evident at a distance of 91 m. Causative factors in this study can be reliably attributed to the platform discharges, since all other factors were constant among stations.

5.4.5 Santa Barbara Channel, California

This study was funded by API and involved an examination of two oil platforms located 3.5 km offshore California in approximately 30 m depth. At the time of the study, the platforms had been operating for about 15 years. Results are presented in Mearns and Moore (1976). Produced water from these platforms is treated onshore at the Carpintria facility, with an ocean discharge (E. Bromley, EPA Region IX; Personal Communication to E. Zimmerman, EPA Headquarters).

Elevated levels of hydrocarbons in sediments were observed around the platforms. Mearns and Moore (1976) concluded that the composition of the hydrocarbons was characteristic of weathered oil and was not indicative of present-day hydrocarbon contamination. Elevated concentrations of zinc were also found in the sediments around the platforms. However, the source of this metal was unclear. Elevated concentrations of vanadium were observed in rockfish.

The study also looked for impacts on benthic organisms. There were no measurable detrimental impacts. However, there was some indication of biostimulation, perhaps due to inputs of organic material from the platform's biofouling community. Again, there was no discharge of produced water at these platforms.

5.5 CATCH AND EFFORT STATISTICS FOR THE GULF OF MEXICO

Trends in catch statistics for commercial fish landings may reflect a number of factors including adequacy of reporting, fishing pressure, natural perturbation, fresh water inflow, and marine pollution effects. These trends are examined here in order to determine if there are any indications that offshore oil and gas operations could be a factor affecting commercial fish and shellfish yields. The National Marine Fisheries Service (NMFS) offices have provided commercial fish landings for the Gulf of Mexico from 1880-1982. The older statistics prior to 1977, are not representative of the Fishery Conservation Zone of 200 miles which came into existence in 1977.

Level-of-effort information which involves estimates of operating units based on the number of fishermen, boats, and gear involved in the catch was also obtained from NMFS. These statistics are published for a number of species in the Gulf of Mexico from 1950-1976. Statistics were compiled for shrimp, red snapper, oyster, and blue crab, since these are some of the most important commercial species.

Although catch-per-unit effort cannot be used as an absolute index of fish abundance, productivity, or health, it is a valuable index for monitoring annual fishery dynamics. The results show that in comparison to the other Gulf states, Louisiana waters have the lowest catch-per-unit effort for shrimp and red snapper based on annual averages from 1950-1976 (Figures 5-3 through 5-5). Louisiana had a higher catch-per-unit effort for oysters in comparison to the other Gulf states (Figure 5-5).

For blue crabs, the catch-per-unit effort statistics are calculated from 1963 when most of the trot lines were replaced by pots. From 1963 to 1976, the catch-per-unit effort for blue crabs is lower in Louisiana offshore waters when compared to the average of the other Gulf states (Figure 5-6 through 5-10).

FIGURE 5-3

SHRIMP LANDING PRODUCTIVITY (CATCH/UNIT EFFORT) IN THE GULF OF MEXICO, 1950–1976

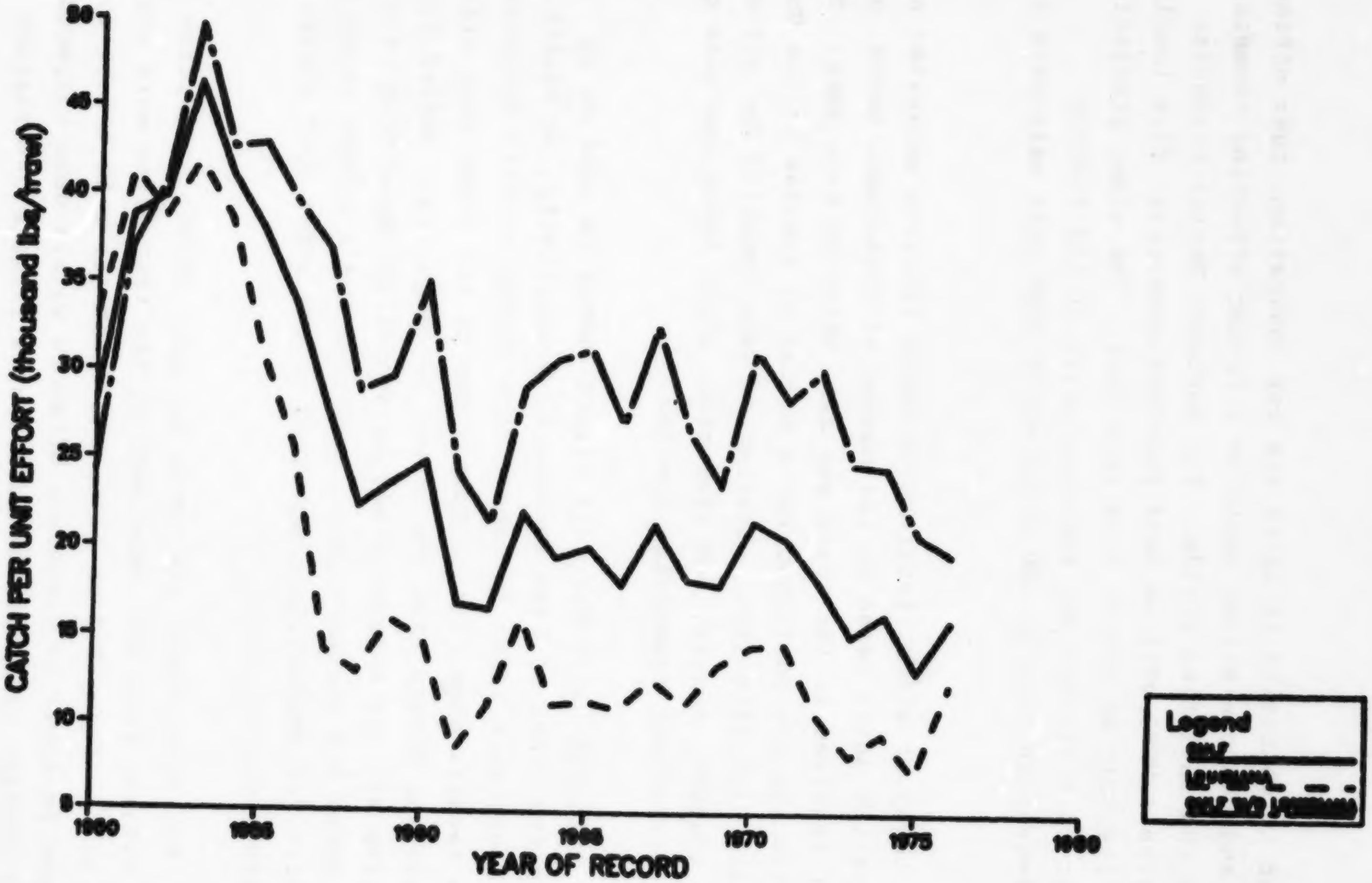
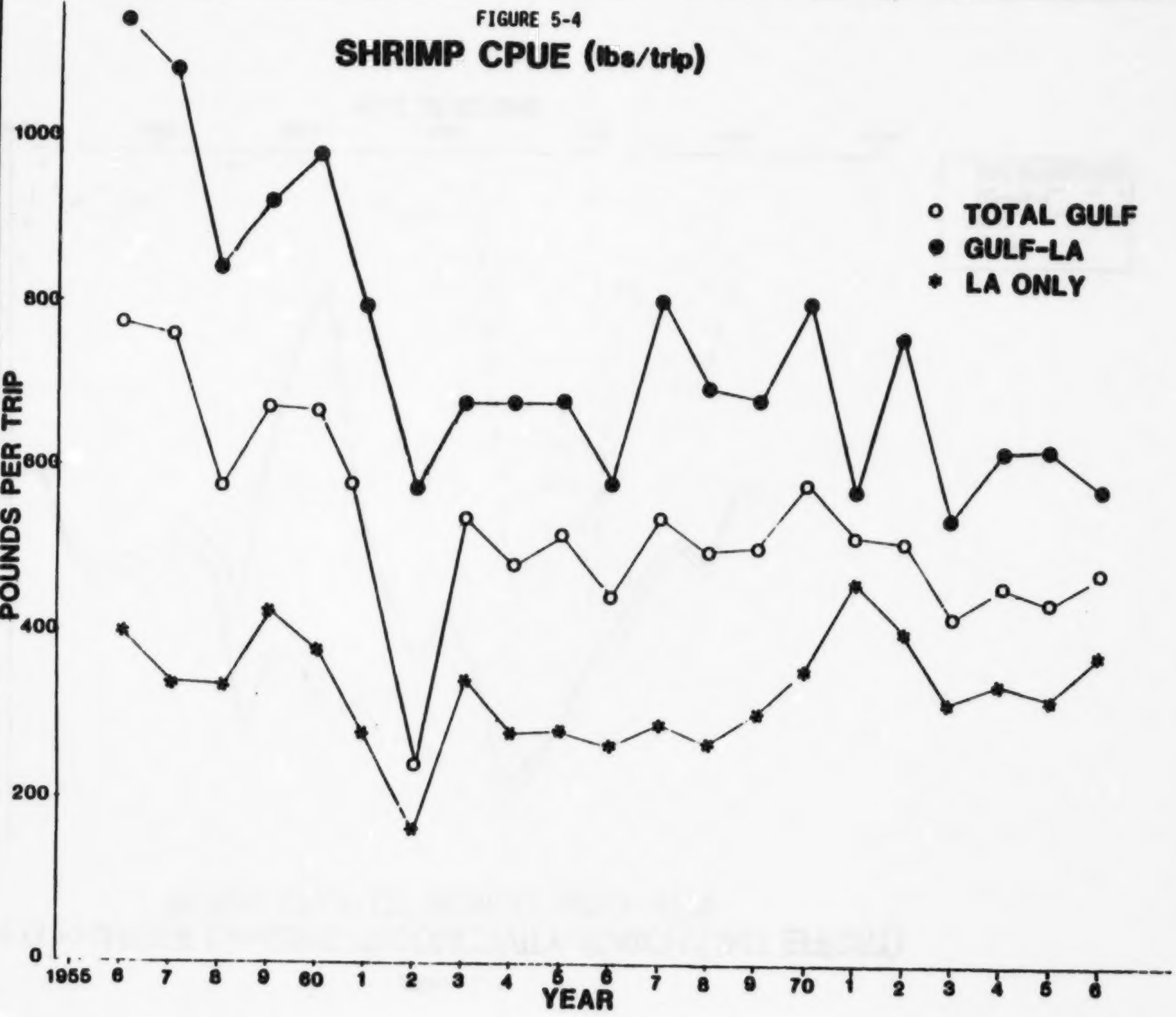


FIGURE 5-4

SHRIMP CPUE (lbs/trip)



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SUBJECT Species analysis BY JKP CHECKED SHEET NO

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FIGURE 5-5

RED SNAPPER LANDING PRODUCTIVITY (CATCH/UNIT EFFORT) IN THE GULF OF MEXICO, 1950–1976

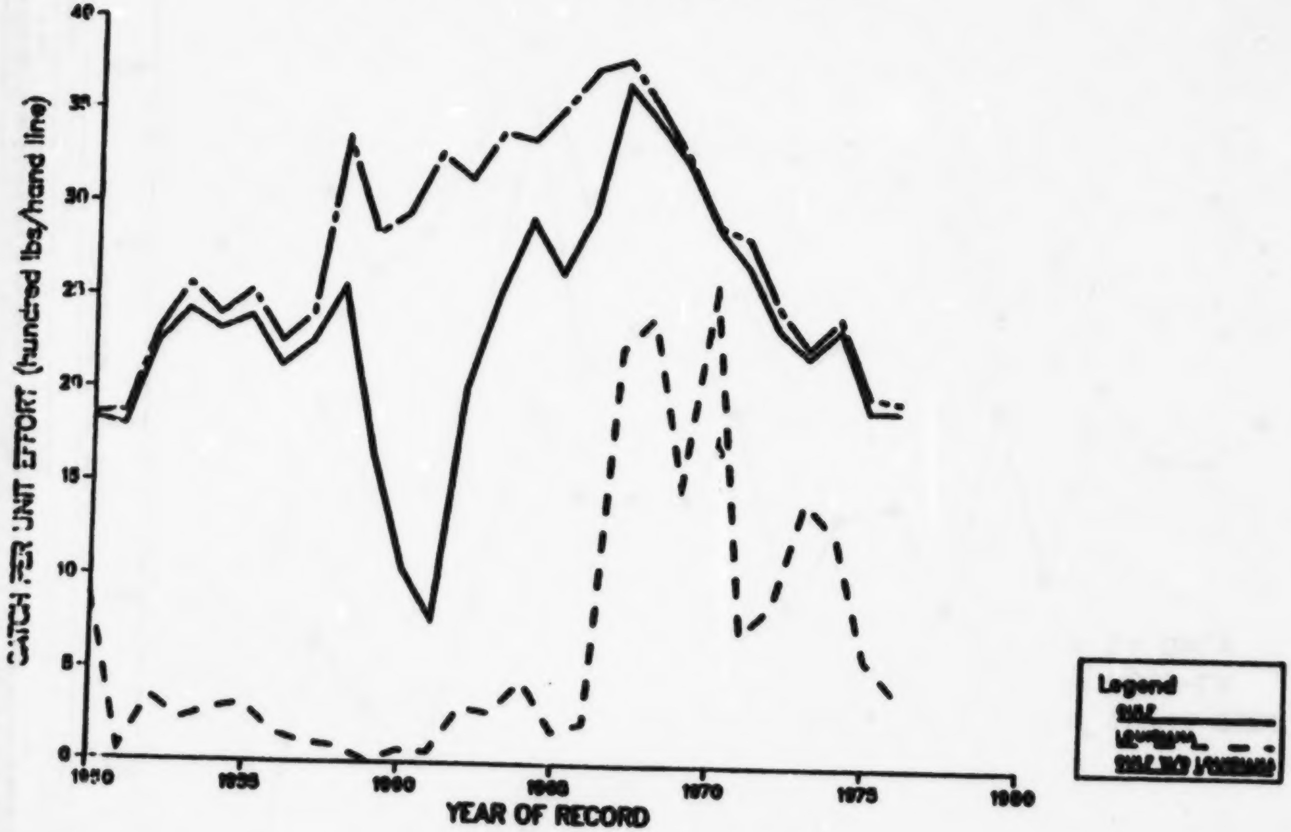

FIGURE 5-6

OYSTER HARVEST PRODUCTIVITY (CATCH/UNIT EFFORT)
IN THE GULF OF MEXICO, 1950–1976

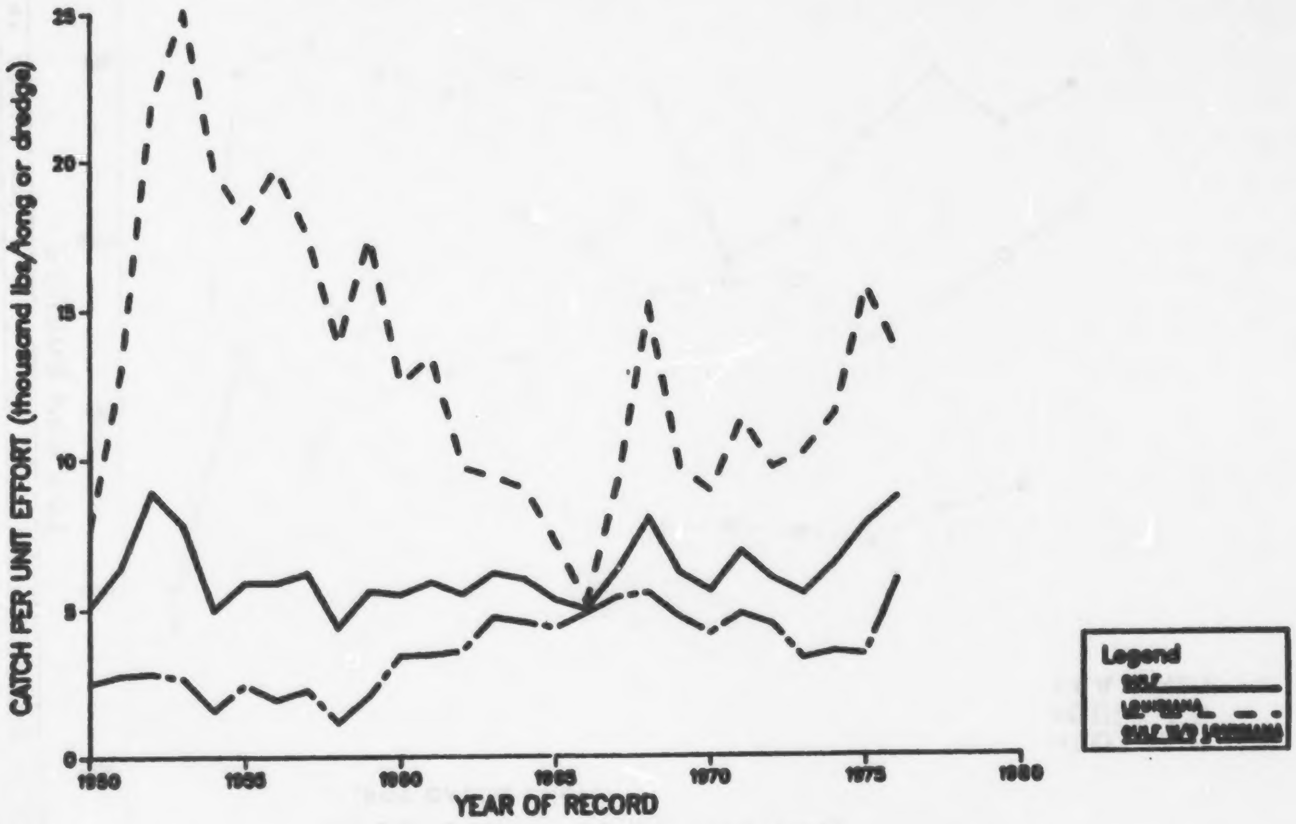

FIGURE 5-7

BLUE CRAB CPUE (lbs/pot)

(POT CATCH ONLY)

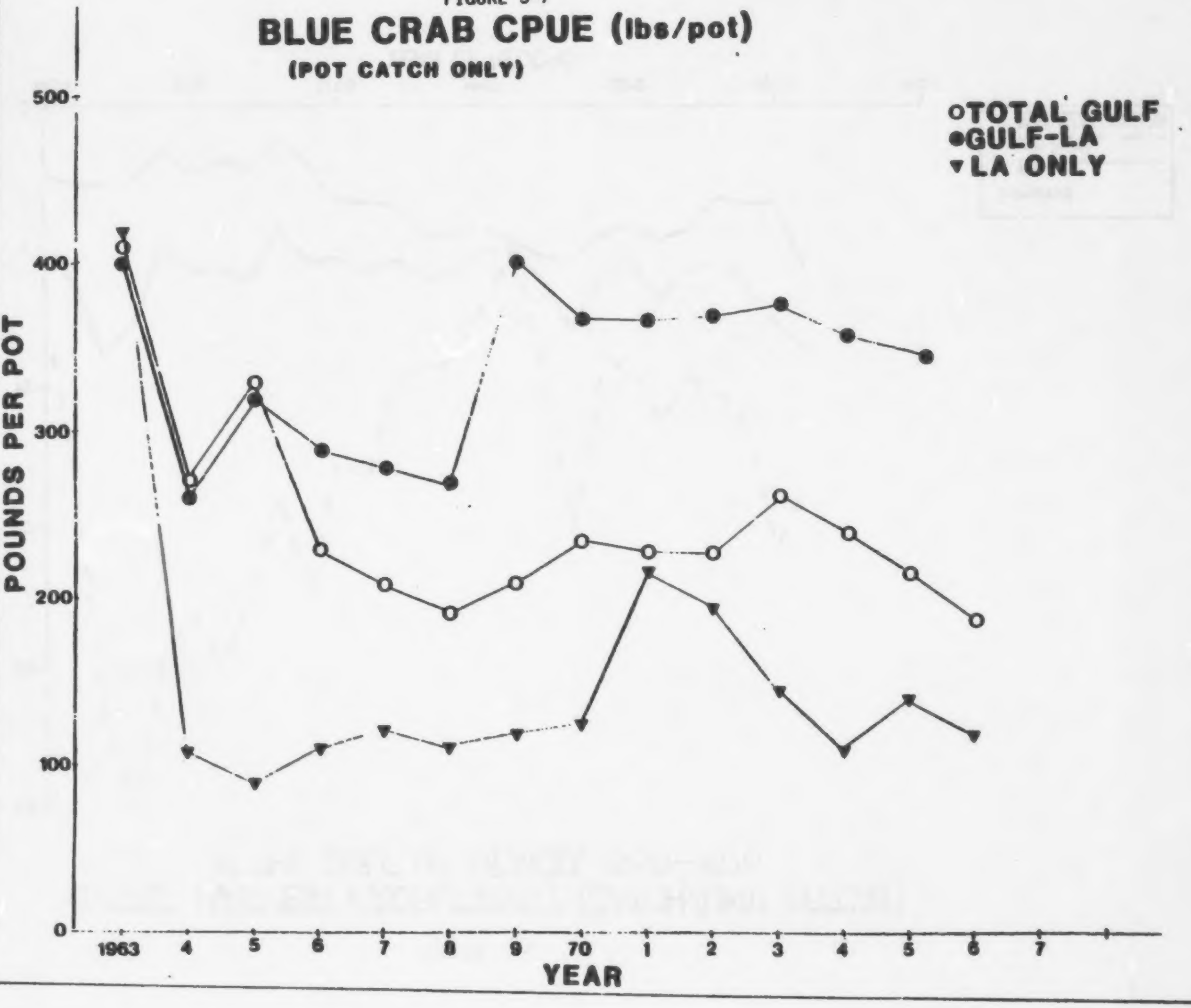

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FIGURE 5-8

BLUE CRAB CATCH AND EFFORT

GULF OF MEXICO

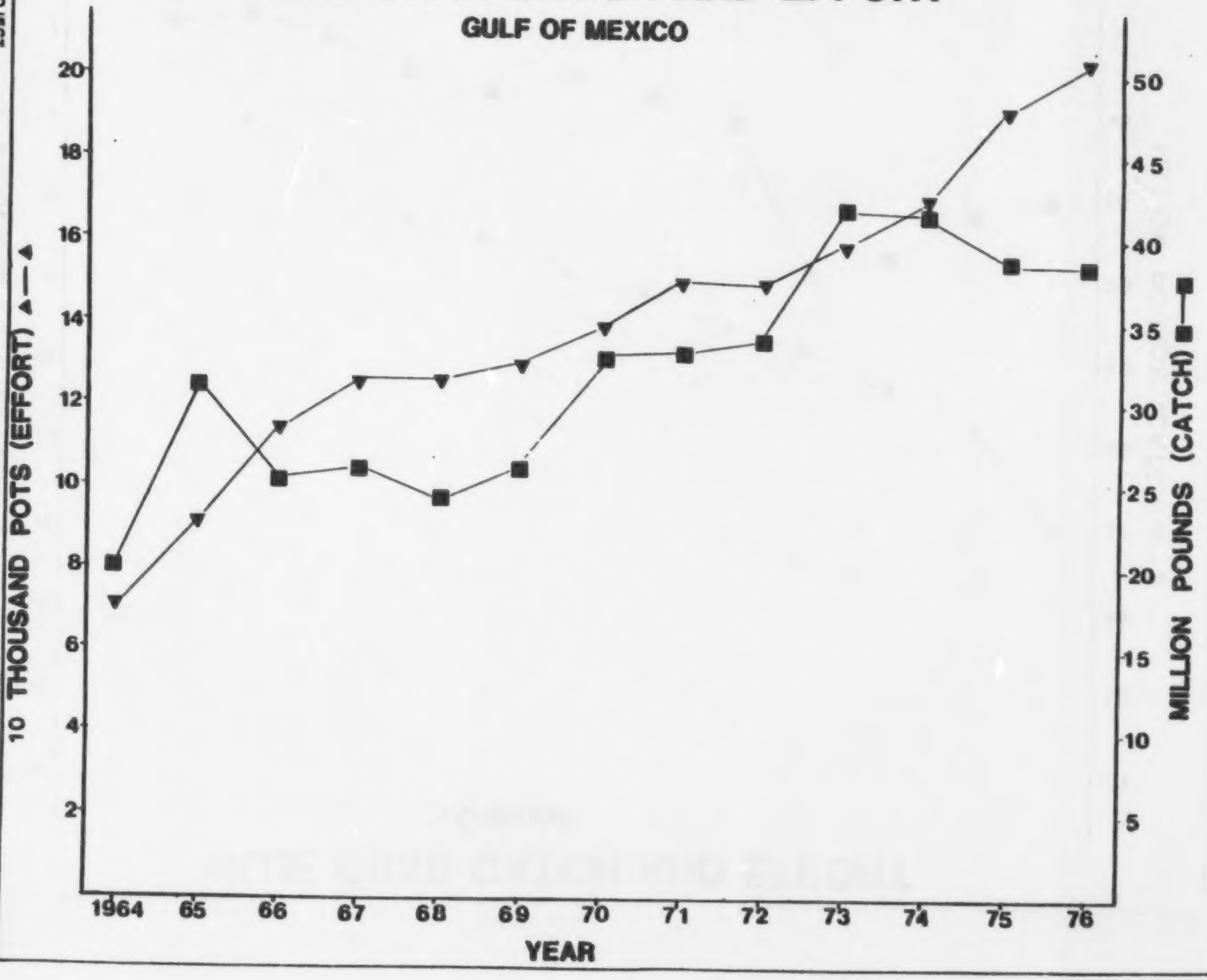

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FIGURE 5-9

BLUE CRAB CATCH AND EFFORT

LOUISIANA

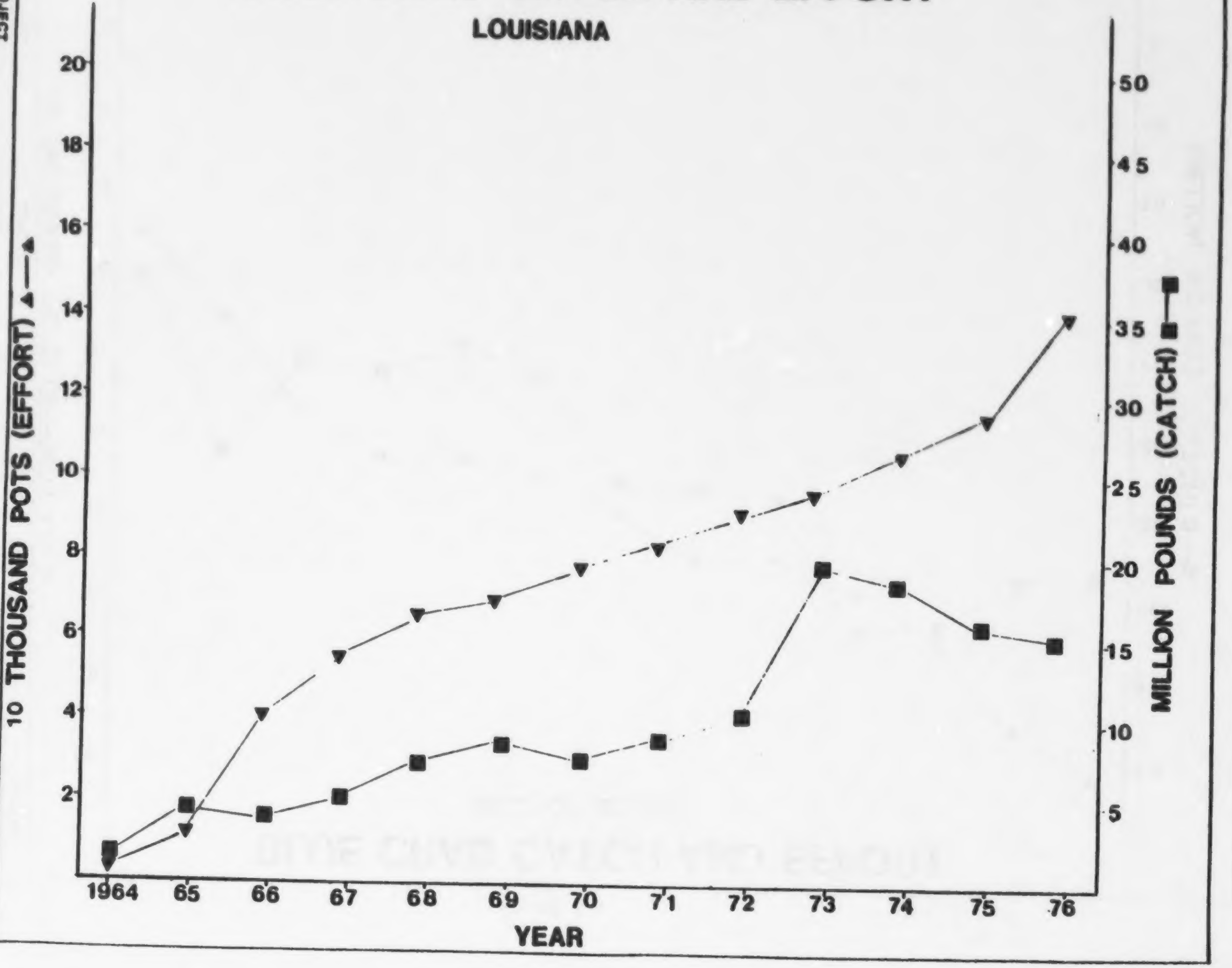

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FIGURE 5-10

BLUE CRAB CATCH AND EFFORT

GULF - LA

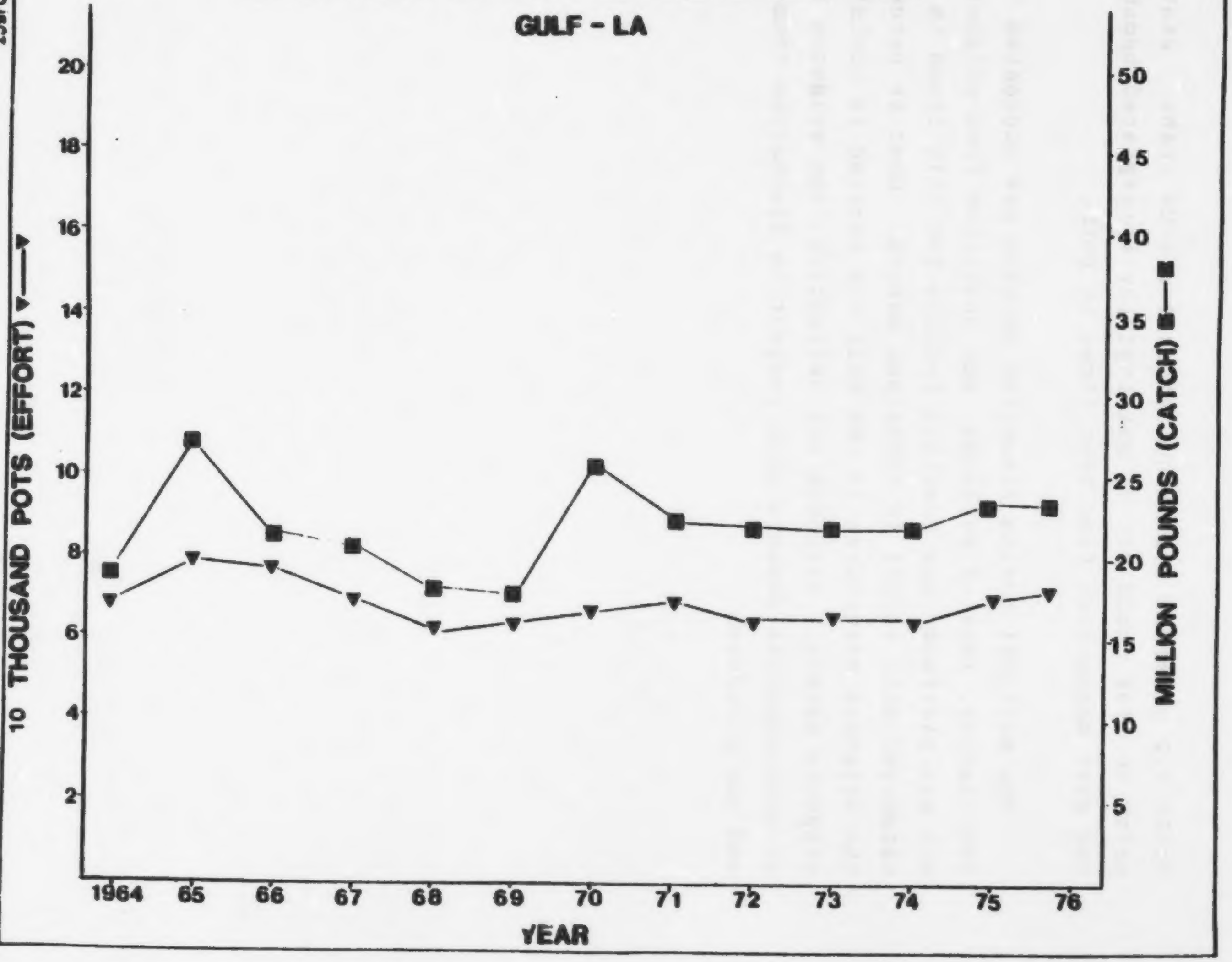

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Table 5-2 presents the calculations for blue crabs. Statistics prior to 1964 could not be meaningfully interpreted because of the gear changeover from trot lines to pots.

The National Marine Fisheries Service has suggested that overfishing, loss of wetlands, and pollution from offshore oil and gas platforms are possible factors for this trend in catch-per-unit effort in Louisiana waters. Over 88 percent of the offshore structures in the Gulf are located in Louisiana offshore waters. Although not definitive, the evidence raises an environmental concern with respect to discharges from oil and gas platforms.

TABLE 5-2 BLUE CRAB CATCH AND LEVEL OF EFFORT
FOR THE GULF OF MEXICO, LOUISIANA, AND THE GULF LESS LOUISIANA

	Gulf of Mexico			Louisiana			Gulf Less Louisiana		
Year	Number of Pots	lbs x 1,000	CPUE[a] (lbs/Pot)	Number of Pots	lbs x 1,000	CPUE (lbs/Pot)	Number of Pots	lbs x 1,000	CPUE (lbs/Pot)
1964	70,145	19,383	276	3,250	2,483	115	66,895	16,900	252
1965	90,085	31,760	352	11,465	4,813	92	78,620	26,947	343
1966	115,010	25,896	225	40,200	4,606	106	74,810	21,290	285
1967	125,611	26,106	207	58,785	5,422	126	66,826	20,684	310
1968	125,611	24,401	190	65,600	6,927	103	60,011	17,474	291
1969	129,026	26,083	202	67,900	8,581	126	61,126	17,502	286
1970	138,700	33,004	236	75,800	7,771	140	63,900	25,233	395
1971	151,240	33,568	223	84,100	10,579	220	67,140	22,989	342
1972	151,220	34,305	227	87,600	12,268	184	63,620	22,037	346
1973	158,480	42,996	271	93,600	20,569	132	64,880	22,427	346
1974	170,345	42,152	247	108,100	19,903	105	62,245	22,249	357
1975	194,330	39,862	205	122,800	16,165	131	71,530	23,697	331
1976	219,919	38,970	177	144,000	15,169	105	75,919	23,801	314

Source: National Marine Fishery Service fishery statistics, 1964-1976.

[a] CPUE = Catch-per-unit effort.

6.0 ECOLOGICAL RESOURCE CHARACTERISTICS OF SHALLOWER MARINE ENVIRONMENTS

6.1 SUMMARY

This section of the report examines ecological resource characateristics of nearshore marine environments. These generally include nursery areas since as larval and juvenile forms are considered the life stages most sensitive to discharges of wastes. The focus was primarily on shallower areas because available information suggests that effects of discharges are more likely to occur there. Information for making these assessments was provided by NOAA as well as reviews of environmental assessments, impact statements, and contacts with state and federal agencies.

For each of the following areas, isobaths were identified which enclosed most or much of the resource/nursery areas. These are listed below:

AREA	ISOBATH
Gulf of Mexico	20 m
Atlantic	20 m
Beaufort Sea	10 m
Bering Sea/Norton Sound	20 m
Cook Inlet/Shelikof Strait	50 m
Bristol Bay/Aleutian Range	50 m
Gulf of Alaska	50 m
California	50 m

6.2 DEPTH DISTRIBUTION OF RESOURCE/NURSERY AREAS

Information presented in Sections 3-5 suggests that shallower areas may be more susceptible to effects of oil and gas discharges than deeper ocean areas. While review of Menzie (1982) and Middleditch (1984) as well as information presented in this report generally support this, it is more difficult to identify a specific isobath beyond which effects would be "substantially less significant." However, it is possible to examine the ecological resource characteristics of shallower ocean environments with a view toward identifying isobaths within which key areas (e.g., spawning, nursery grounds, fishing banks) occur. These shallower areas constitute regions that might be considered for an additional margin of protection. An assessment was therefore made of the shallower water ecological resources of these areas.

Information on species distribution for the Gulf of Mexico and the East Coast has been compiled for EPA by the Ocean Assessments Division of the National Oceanic and Atmospheric Administration (NOAA) based on computerized species distribution data from the National Marine Fisheries Service (NMFS). The list of species was selected from Tables 4-13 thru 4-16 of Section 4 on potential acute and chronic effects from various pollutants found in produced waters. The following 15 species which were contaminated with petroleum hydrocarbons during the Buccaneer Field study were also included in the analyses:

Archosargus probatocephalus (sheepshead)
Centropristis philadelphica (rock sea bass)
Chaetodipterus faber (Atlantic spadefish)
Cynoscion arenarius (sand seatrout)
Lutjanus campechanus (red snapper)
Micropogon undulatus (Atlantic croaker)
Pomatomus saltatrix (bluefish)
Porichthys porosissimus (Atlantic midshipman)
Prionotus rubio (blackfin searobin)
Saurida brasiliensis (largescale lizardfish)
Stenotomus caprinus (longspine porgy)
Syacium papillosum (dusky flounder)
Symphurus plagiusa (blackcheek tonguefish)
Synodus foetens (inshore lizardfish)
Urophycis floridanus (southern hake)

Nursery areas were chosen as key "resource areas" for this analysis because they are where sensitive life stages (pre-adult and post-larval) are expected to occur. NOAA did not have some of the species listed above in their database or many invertebrate species such as barnacles, polychaetes, copepods, snails, etc. in their database for the Gulf of Mexico or East Coast. Most of the available data is on commercially important fish species and invertebrates, which vary by region. Based on the information made available by NOAA a significant portion of the nursery areas for the selected fish and invertebrate species in the Atlantic and Gulf regions are located within the 20 m (66 feet) isobath.

Tables 6-1 and 6-2 show the percentage of the nursery areas that would be protected by the designated areas (estuaries, state waters, 10 m-2000 m water depths) for the Gulf of Mexico and for the East Coast (estuaries, state waters, 20 m-2000 m water depths).

Key resource (nursery) areas for the West Coast and Alaskan analyses are more difficult to define because of the lack of a computerized data base. NOAA only has preliminary data on these areas and this could not be used at this time, except the Bristol Bay analysis which is based on preliminary draft information from NOAA. For the other analyses, information was obtained from Environmental Impact Statements on offshore lease sales. In addition, Ocean Discharge Criteria evaluations were examined, and NMFS and state officials in Alaska and California were contacted in order to provide information on these areas.

Section 6.3 discusses information for the Beaufort Sea, the Bering Sea, Cook Inlet/Shelikof Strait, Gulf of Alaska, and Bristol Bay which are all in Alaska. These regions were selected because of new platform projections or potential development in these areas. These areas constitute distinct transition zones between subarctic and arctic environments. Each supports distinct ecological communities. The vast differences in physical and biological environments of these five regions necessitated separate analyses of their marine resources. These analyses indicate that a 10 meter isobath in the Beaufort Sea, a 20 meter isobath in the Bering Sea (Norton Sound), and a 50 meter isobath in Cook Inlet/Shelikof Strait, Gulf of Alaska, and Bristol Bay would provide significant protection of key vulnerable life stages for important commercial and subsistence species.

TABLE 6-1

GULF OF MEXICO
CUMULATIVE PERCENT OF NURSERY AREA CELLS INCLUDED IN THE ANALYSIS AREA

Species	Estuaries	State Waters	10m	20m	60m	100m	200m	2000m
Fish								
Atlantic Croaker	39	62	70	99	100	100	100	100
Sand Seatrout	88	86	98	100	100	100	100	100
Longspine Porgy	25	47	54	98	100	100	100	100
Bluefish	72	87	95	100	100	100	100	100
Red Snapper	17	37	38	61	100	100	100	100
Dusky Flounder	8	22	21	37	82	96	100	100
Invertebrates								
Brown Shrimp	83	90	98	100	100	100	100	100
Pink Shrimp	72	89	97	99	99	99	99	99
White Shrimp	83	86	98	100	100	100	100	100
American Oyster	64	85	95	99	100	100	100	100
Blue Crab	27	47	49	75	100	100	100	100
Total Fish	42	57	63	83	97	99	100	100
Total Invertebrates	66	79	88	94	100	100	100	100
Total Fish and Invertebrates	52	67	74	88	98	99	100	100

TABLE 6-2

EAST COAST
CUMULATIVE PERCENT OF NURSERY AREA CELLS INCLUDED IN THE ANALYSIS AREA

Species	Estuaries	20m	60m	100m	200m	2000m
Fish						
Bluefish	70	99	100	100	100	100
Striped Bass	94	100	100	100	100	100
Atlantic Croaker	53	98	100	100	100	100
Winter Flounder	46	64	96	100	100	100
Invertebrates						
Hard Clam	42	92	100	100	100	100
Soft Clam	55	82	100	100	100	100
American Oyster	60	96	100	100	100	100
American Lobster	11	29	42	61	81	100
Total Fish	66	90	99	100	100	100
Total Invertebrates	42	75	86	90	95	100
Total Fish and Invertebrates	54	83	92	95	98	100

Section 6-4 summarizes the available information for California. Initial examination of the bathymetric maps indicate that the 50 meter isobath will protect key areas of ecological resource significance, including most of the known nursery areas.

6.3 ALASKAN RESOURCE AREAS

Most future oil and gas exploration and production in Alaska will be concentrated in several regions: the Beaufort Sea, the Bering Sea (Norton Sound), Bristol Bay, Cook Inlet/Shelikof Strait, and the Gulf of Alaska (Figure 6-1). These five regions constitute distinct transition zones between subarctic and arctic environments. Each supports a distinct ecological community.

6.3.1 Beaufort Sea

The Beaufort Sea is located on the northern coast of Alaska in the Arctic Ocean. The Diapir Field shown in Figure 6-2 is the lease area under development. The area is characterized by a low energy regime with little movement and mixing of sediments. The biological resources of the area are concentrated in three distinct zones. The nearshore zone, a region of annual shorefast ice, includes waters less than two meters deep and any enclosed or protected waters. The inshore zone includes water from two to 20 meters deep and the offshore zone includes all waters greater than 20 meters deep.

The Beaufort Sea/Arctic Ocean area is characterized by a food web in which the zooplankton and epifauna (mysid shrimp,

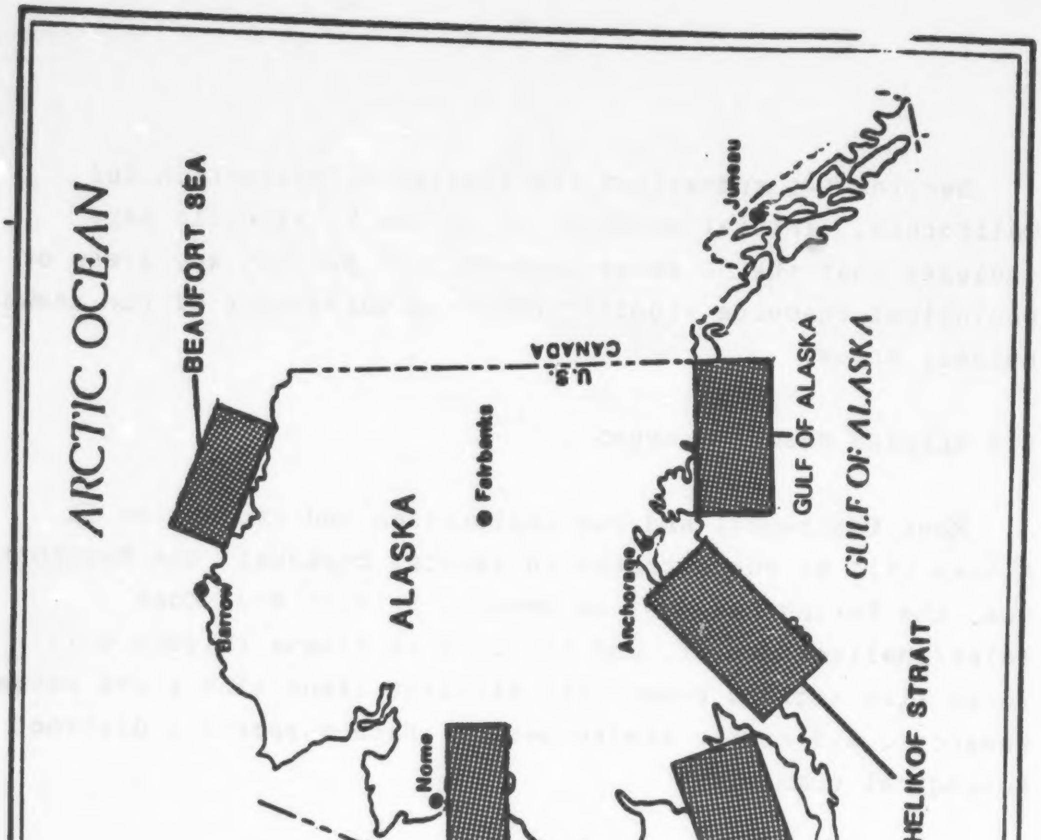


FIGURE 6-1 AREAS OF FUTURE OIL AND GAS DEVELOPMENT IN ALASKA

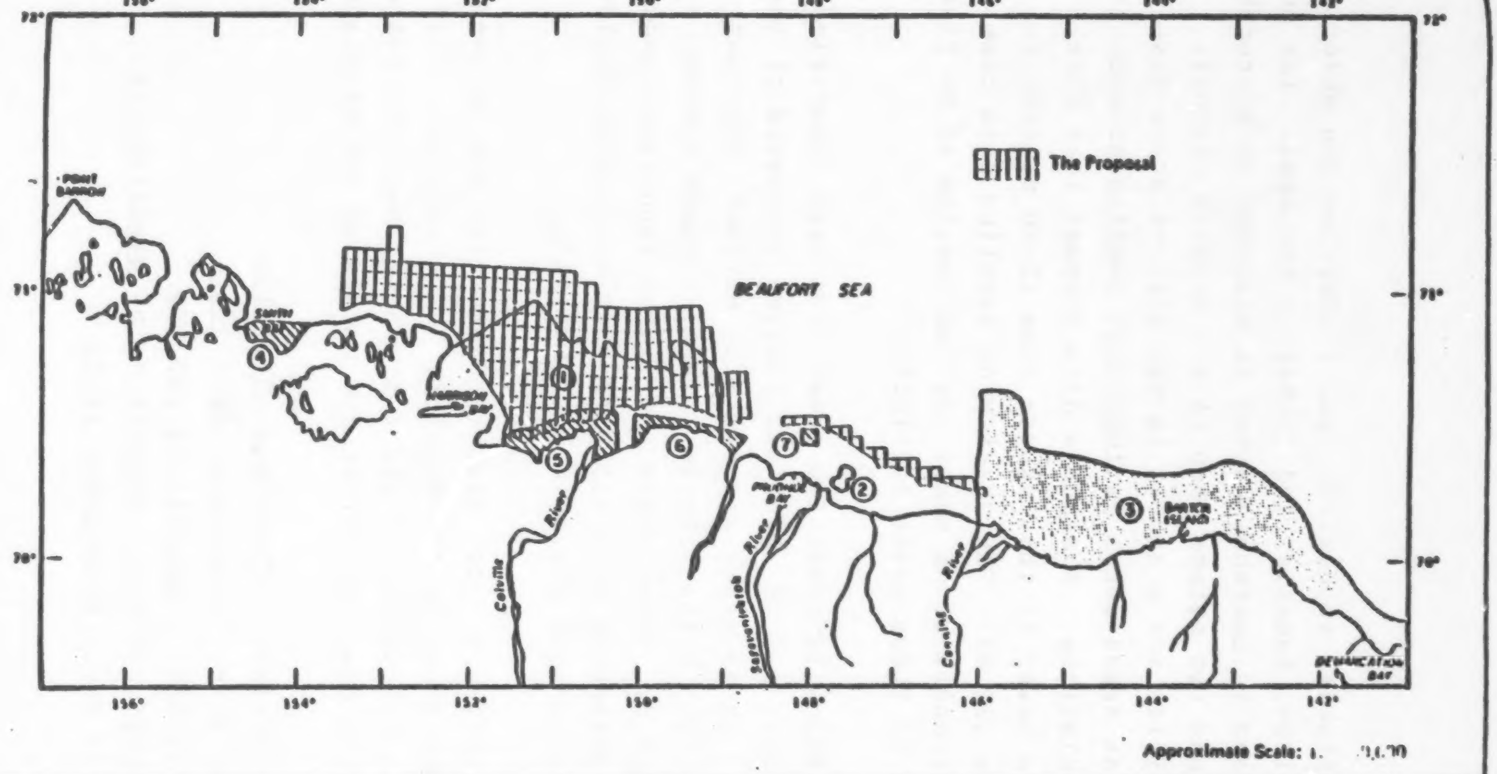


FIGURE 6-2 CANDIDATE MARINE SANCTUARIES AND POTENTIAL NATIONAL NATURAL LANDMARKS IN OR ADJACENT TO THE DIAPIR FIELD

—LEGEND—

☐ Proposed Marine Sanctuaries
1 Harrison Bay/Simpson Lagoon
2 Stefansson Sound Boulder Patch
3 Offshore Arctic Wildlife Range

▨ Potential National Natural Landmarks (only water areas mapped)
4 Smith Bay
5 Colville River Delta
6 Simpson Lagoon
7 Cross Island

SOURCES:
1. NOAA Preliminary Candidate Marine Sanctuary Site Listing
2. BLM, 1982, Graphic 10.

copepods, amphipods, euphasiids, etc.) comprise the major food resource of birds, mammals, and fishes in the area. The bulk of the fish feed in nearshore areas in enclosed or protected waters less than two meters deep (i.e., Simpson Lagoon). Epifauna densities are greatest in the inshore areas (two to 20 meters). These areas serve as important feeding grounds for nearshore populations. Available data suggest that fish densitites are lower in the inshore zone (2-20 m) than the nearshore zone (22 m). The paucity of sampling data from the inshore and offshore zones makes any conclusions as to fish distributions in these areas difficult.

Five biologically sensitive areas have been identified in the Beaufort Sea, all of which are located shoreward of the 10 m isobath. These areas are the Salt Marshes; Harrison Bay/Colville River Delta; Thetis Island; Simpson Lagoon; and the Boulder Field. These areas are either important feeding grounds for indigenous fish and bird species or like Boulder Field, comprise unique biological communities.

The following are "key" fish (commercially and in terms of ecosystem importance) in the Beaufort Sea ecosystem. They comprise 91 to 98 percent of all fish in the Beaufort Sea and their density is greatest within 100 meters of the mainland.

Arctic cisco - Coregonus antunalis
Least cisco - Coregonus sardinella
Arctic char - Salvelinus alpinus
Fourhorn sculpin - Myoxocephalus quadricornis
Arctic cod - Boreogadus saida

The Arctic cisco, Least cisco and Arctic char are anadromous species which return to their natal streams for spawning. The Fourhorn sculpin and Arctic cod are marine fish. During the open-water season, anadromous and marine fish appear to prefer and widely use nearshore habitats as feeding and rearing areas, especially the enclosed or protected lagoons and bays. Most fish retreat to the river drainage during the winter months. The marine fish appear to move offshore during the winter months. In late winter Arctic cod are up to thirty times more abundant 100 miles offshore than nearshore.

The 10 m isobath, which generally falls within the state waters (three mile geographical line) except in the Harrison Bay/Colville River Delta region, includes the major feeding grounds and nursery areas of the above key fish species and the various "biologically sensitive areas" previously mentioned. This isobath also includes the zone of maximum epifauna density, and as such is an important source of mysids, amphipods and copepods which migrate into shallower, nearshore waters and provide a crucial base to the marine food web. Thus, the 10 meter isobath will bound much of key resource areas within the Beaufort Sea.

6.3.2 Bering Sea

The Bering Sea separates the western coast of Alaska from Siberia. It is an important migratory channel for many species of marine mammals and birds. There are several proposed lease areas within the Bering Sea. The open water lease areas, such as Navarin Basin, generally lie in deep waters (70 to 2,800 m) and are not likely to support critical nursery habitats. There is some indication of spawning activity in these waters but species life history distribution information is lacking for these areas. The lease area proposed for Norton Sound lies in shallower waters which are important nursery habitats for several commercial species (see Figures 6-3 and 6-4).

6.3.2.1 Norton Sound

Norton Sound is an important transition zone between subarctic and arctic marine communities. The area is characterized by two separate energy regimes and water types. The shallow coastal waters of Norton Sound (20 meters) are a relatively warmer, low salinity, low energy environment strongly influenced by the Yukon and Kuskokwim Rivers. The western Bering Sea shelf waters are a colder, more saline, high energy environment.

The Yukon-Kuskokwim River Delta is considered a vulnerable coastal area which is a critical habitat for North America's largest run of king salmon. Approximately one-third of this delta region comprises the Clareance Rhode National Wildlife Refuge. The delta is also critical to the natives' subsistence harvest.

Important commercial fisheries in Norton Sound include five North American salmon (pink, chum, chinook, cohoe, and king), Pacific herring, and king crab. Other species in Norton Sound which are important food resources for marine birds and mammals found in the area include saffron cod, Arctic cod, starry flounder, rainbow smelt, and tanner crab.

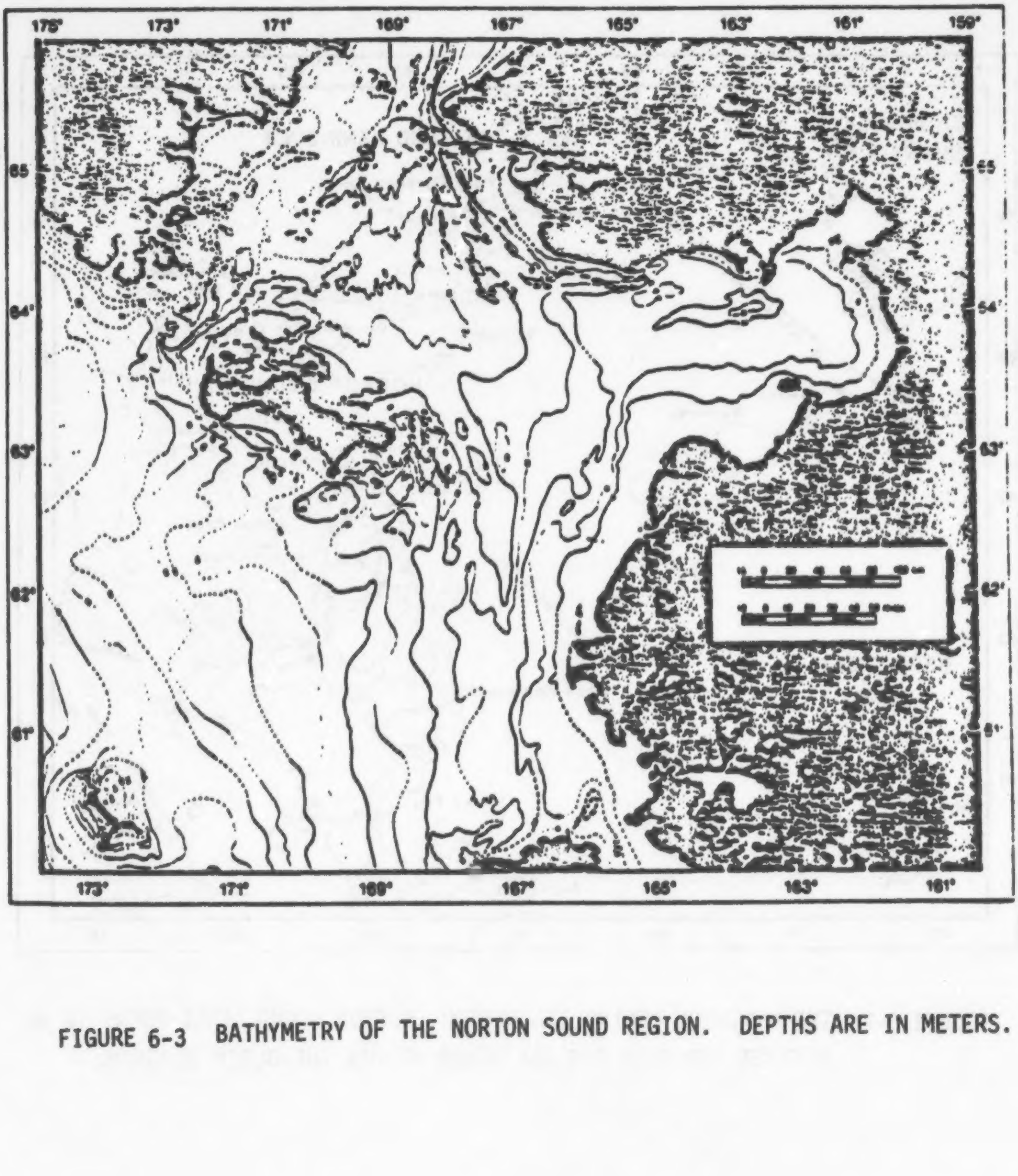


FIGURE 6-3 BATHYMETRY OF THE NORTON SOUND REGION. DEPTHS ARE IN METERS.

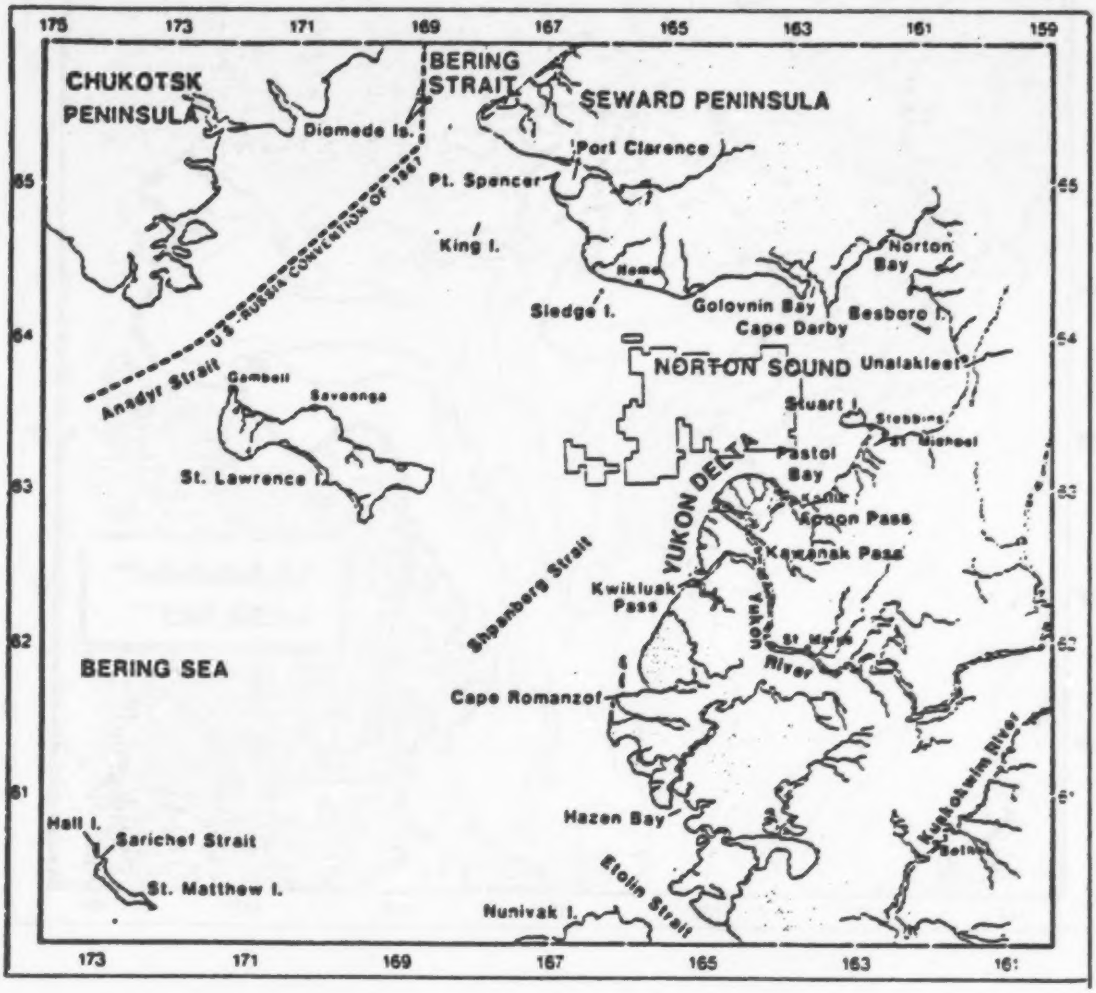


FIGURE 6-4 THE NORTHERN BERING SEA REGION. NORTON SOUND LEASE AREAS TO BE OFFERED FOR SALE ARE CONTAINED WITHIN THE BLOCK DIAGRAM.

The 20 m isobath (Table 6-3) incorporates most of the Norton Sound area east of 165^{o}W longitude (the area west of a line which connects the mouth of the Yukon River on the southern coast and Cape Nome on the northern coast). This isobath encompasses most of the following important biological habitats:

- Critical Yukon-Kuskokwim Delta habitat (including wildlife refuge)
- Salmon nursery areas and initial smelt migration areas
- Important king crab mating, molting and rearing areas
- Pacific herring nursery areas
- Arctic cod spawning grounds
- Areas of concentration for saffron cod, starry flounder and rainbow smelt (all collected primarily shoreward of the 25 m isobath)

6.3.3 Cook Inlet/Shelikof Strait

Cook Inlet/Shelikof Strait is located on the southern coast of Alaska and is an inlet of the Gulf of Alaska (Figure 6-5). Cook Inlet is typically a very high energy environment with a great deal of mixing and unstable bottom contours. Due to shifting sand bars, the depth contours of Cook Inlet are not always consistent. The environment is such that intertidal communities have been documented at depths as great as 65 meters. Most oil and gas activity occurs in southern Cook Inlet, south of Anchor Point.

The important habitats of Cook Inlet, i.e., areas utilized by a disproportionate abundance of individuals and/or species,

TABLE 6-3 SPAWNING AND NURSERY AREAS FOR MAJOR COMMERCIAL FISH AND INVERTEBRATE SPECIES IN NORTON SOUND, ALASKA

Species	Reproductive/nursery area	Approximate % of nursery area within the 20 m isobath
Fish		
Pink salmon Chum salmon Chinook salmon Coho salmon	Anadromous species associated with Yukon River Delta which spawn in freshwater streams; young move along coast during initial two months of migration.	100%
Pacific herring	Spawns in subtidal region east of 164°W longitude; eggs adhere to inshore vegetation.	100%
Invertebrates		
King crab	Shallow, subtidal region (0-20 m) extensively used for spawning, molting, breeding, feeding, and rearing of the young. Entire coastal region from Yukon Delta to Cape Rodney may be important nursery habitat.	100%
Tanner crab	Juvenile crabs found throughout the area, indicating this may be an important nursery area for this crab.	80%

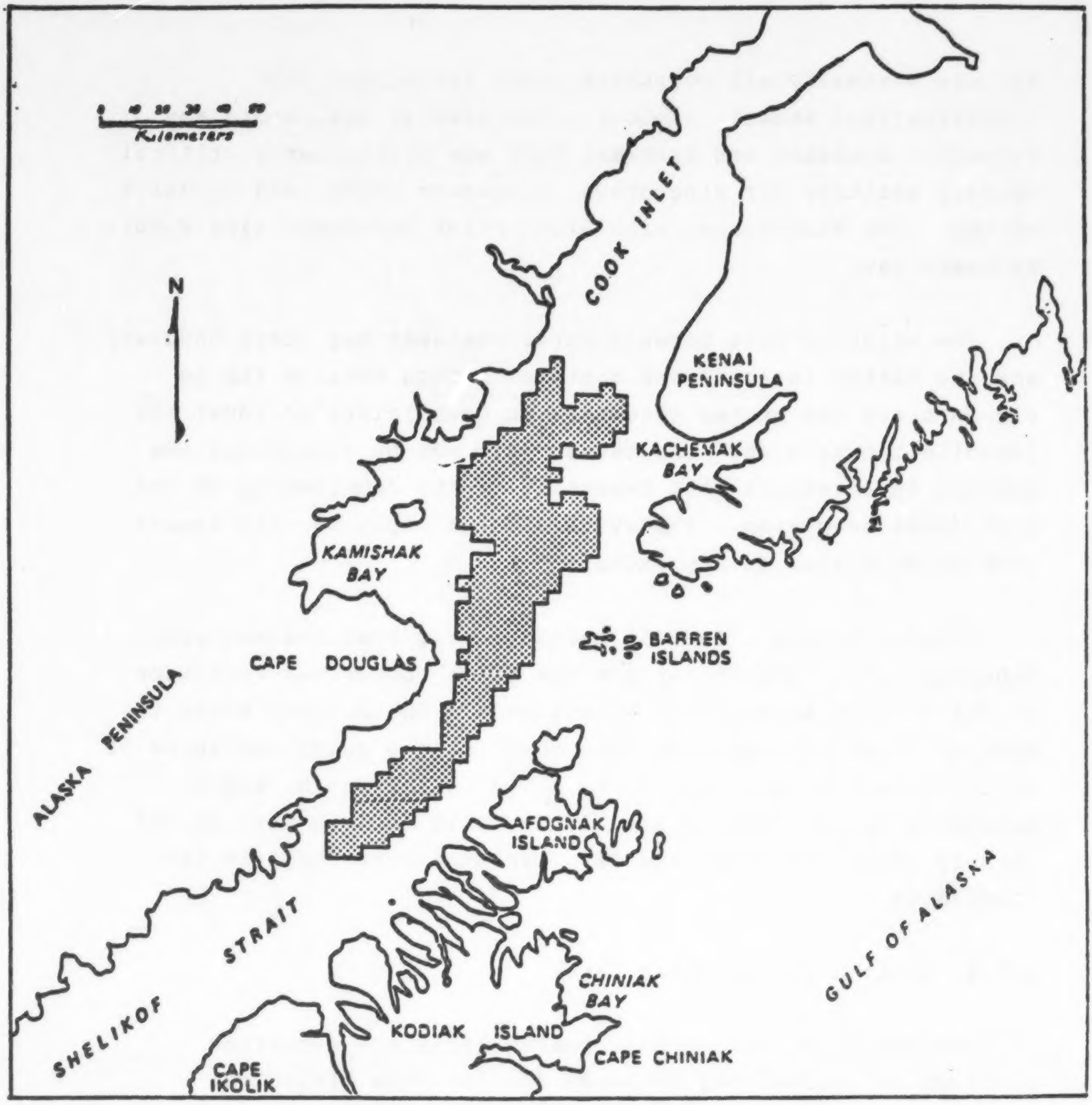


FIGURE 6-5 OCS LEASE SALE 60:
LOWER COOK INLET — SHELIKOF STRAIT.

include virtually all nearshore areas throughout Cook Inlet/Shelikof Strait, including the coastal embayments and islands. Kamishak and Kachemak Bays are particularly critical nursery habitats for king crabs, dungeness crabs, and pandalid shrimp. The king/tanner crab Bluff Point Sanctuary lies within Kachemak Bay.

The offshore area between outer Kamishak Bay (Cape Douglas) and the Barren Islands area contains a high density (up to eleven times the number elsewhere in Cook Inlet) of adult and juvenile tanner crab. The tanner crab may be considered the benthic invertebrate most important to the functioning of the Cook Inlet ecosystem. The average water depth in this tanner crab nursery area is approximately 150 m.

Salmon, halibut, Pacific herring, king crab, tanner crab, dungeness crab, and shrimp are the major commercial fisheries in the Cook Inlet/Shelikof Strait area. The nursery areas for most of these species have been described as being nearshore or in intertidal areas (Table 6-4). The 50 m isobath, which generally falls within state waters, will enclose most of the nursery areas for these species (except tanner crab) in the study area.

6.3.4 Bristol Bay/Aleutian Range

The southeast Bering Sea, particularly the estuarine shallows of Bristol Bay is known for its high biological activity. This area of Alaska is perhaps the most controversial with regard to offshore oil and gas development is due to its close proximity to salmon and crab fishing areas, natural wildlife refugees and State of Alaska critical habitat areas.

TABLE 6-4 VITAL REPRODUCTIVE AND NURSERY AREAS FOR IMPORTANT COMMERCIAL FISHERIES IN COOK INLET AND SHELIKOF STRAIT

Species	Reproductive/Nursery area	Approximate % of nursery area within the 50 m isobath
Fish		
Salmon	Freshwater streams and rivers; smelt migrate along coastal area.	100%
Pacific herring	Spawn along shallow, intertidal zone on nearshore vegetation.	100%
Halibut	Demersal larvae remain inshore for one to three years.	90%
Invertebrate		
King crab	Typically rear young in shallow (0 to 20 m) water of Kamishak and Kachamak Bays and nearshore areas of Kodiak Island and Shelikof Strait.	80%
Dungeness crab	Nursery areas include coastal waters and embayments less than 60 m deep. Juveniles collected in mid-Kachemak Bay and nearshore Kamishak Bay and Shelikof Strait.	90%
Tanner crab	Outer Kamishak Bay and between Cape Douglas and the Barren Islands.	50%
Pandalid shrimp	Inner Kachemak Bay and nearshore areas of Shelikof Strait near Cape Gull.	100%

The eastern and southern margins of Bristol Bay are bordered by the Alaska Peninsula. The Aleutian Range forms the backdrop from which the elevation drops to a coastal plain. This plain extends 16 to 30 km to a coast which is typified by sandy beaches and brackish coastal lagoons. Bars, spits, and barrier islands are numerous throughout the nearshore region. To the north the shoreline includes several large estuaries and lagoons, interspersed with sandy beaches and coastal bluffs.

The Pribilof Island group consists of two major islands, St. George and St. Paul, and several small inlets. The coastline of St. Paul Island consists generally of unstable sandy beaches. The coastline of St. George Island is characterized by steep bluffs and cliffs.

The coastal habitat along the Aleutians is noted for its high infaunal standing stocks, especially clams. Crabs and demersal fish, especially the juveniles of many species, are abundant in coastal waters. The Bristol Bay habitat is abundant with pacific herring, pink salmon, chum salmon, coho salmon, sockeye salmon, chinook salmon, saffron cod and other species. These species and numerous other species have nursery areas in this region.

The 50 m isobath, which generally falls inside of state waters along the Aleutian Islands and Alaska Peninsula, will enclose most of the nursery areas for salmon and other important commercial fish as well as invertebrates like crabs and shrimp (Table 6-5).

TABLE 6-5
NURSERY AREAS LOCATED IN BRISTOL BAY/ALEUTIAN ISLANDS AREA

Species	Approximate % of Nursery Area within the 50 m Isobath	
Crangonid Shrimp	90%	
Large Crangonid Shrimp	100%	
Other Pandalid Shrimp	50%	
Korean Hair Crab	50%	overall nurseries
	100%	major nursery areas
Red King Crab	100%	for juveniles less than 40 mm carapace
Tanner Crab	50%	
Chalky Macoma	50-90%	
Pacific Herring	100%	
Pink Salmon	100%	
Chum Salmon	100%	
Coho Salmon	100%	
Sockeye Salmon	100%	
Chinook Salmon	100%	
Capelin	100%	for spawning & small juveniles
	50%	for larger juveniles
Eulachon	100%	for spawning & small juveniles
	100%	for larger juveniles
Rainbow Smelt	100%	
Saffron Cod	100%	for spawning & small juveniles
	50-90%	for larger juveniles
Pacific Cod	50%	for juveniles & spawning areas
Walleye Pollock	50%	
Yellowfin Sole	100%	of spawning & small juveniles
	50%	of larger juveniles
Alaska Plaice	100%	of juveniles
Starry Flounder	70%	
Rock Sole	50%	
Pacific Halibut	50%	

6.3.5 Gulf of Alaska

The Gulf of Alaska is bounded on the north by the coastline of Alaska and on the south by the North Pacific Ocean. The coastal topography is rugged. The Alaskan current is continuous throughout the Gulf. However, in the Gulf of Alaska the current intensifies and forms a concentrated stream along the shelf break called the Alaska Stream.

Large populations of commercially valuable crabs, shrimp, molluscs, salmon, herring, pollock, halibut, and other groundfish use these waters as their principal spawning, rearing, and foraging grounds. Coastal fiords and embayments are the nursery areas for many key pelagic (e.g., herring, capeline, salmon) and benthic (e.g., halibut, pollock, cod) fishes. Migratory routes of commercially important stock from other Alaskan regions (e.g., Bristol Bay sockeye salmon, Unimak Pacific Ocean perch, southeastern Alaskan Pacific halibut) lie along the outer continental shelf of this area. Some of the principal species inhabiting the coastal regions of the Gulf of Alaska are shown in Table 6-6.

Juvenile shrimp are found in waters less than 40 m deep, but live in greater depths in summer. The salmon and trout are commonly found in oceanic waters and estuaries and in freshwater watersheds draining into the Gulf. Pink, sockeye and chum salmon are widely distributed in the Gulf of Alaska. Their nursery areas are closer to the shoreline. A water depth of 50 meters should enclose a substantial portion of the nursery areas in this region.

TABLE 6-6

NURSERY AREAS FOR MAJOR COMMERCIAL FISH AND INVERTEBRATE SPECIES IN THE GULF OF ALASKA, ALASKA

Species	Approximate Percent of Nursery Area with the 50 m Isobath
Pink Salmon	40 %
Chum	<50 %
Sockeye	90 %
Coho	80 %
Chinook Salmon	100 %
Rainbow Trout	100 %
Cutthroat Trout	80 %
Pacific Herring	40 %
Pink Shrimp	80 %
Sidestripe Shrimp	80 %
Ocean Pink Shrimp	80 %

6.4 MARINE RESOURCE AREAS OFF CALIFORNIA

The California offshore area (Figure 6-6) is a structurally complex region typified by a highly irregular topography of deep basins, islands, submarine canyons and rocky intertidal regions. In comparison with the Gulf of Mexico region, the continental shelf off California (200 m isobath) is fairly narrow with a width of less than two miles in some areas.

The biological communities of the California Bight are also extremely complex, consisting of many species and assemblages which are difficult to summarize. For the purposes of this analysis, the nursery areas of commercially important fish and shellfish were considered. Table 6-7 summarizes the available information concerning the distribution and depth of spawning and nursery areas. The values in this table are based on a limited database of distribution information and, at best, represent approximations.

There are four types of areas of special biological concern which are legally defined and controlled by the State of California in an effort to protect intertidal and shallow subtidal areas which contain unique or extraordinary biological communities:

- Ecological reserves
- Marine life refuges
- Reserves
- Areas of special biological significance (ASBS).

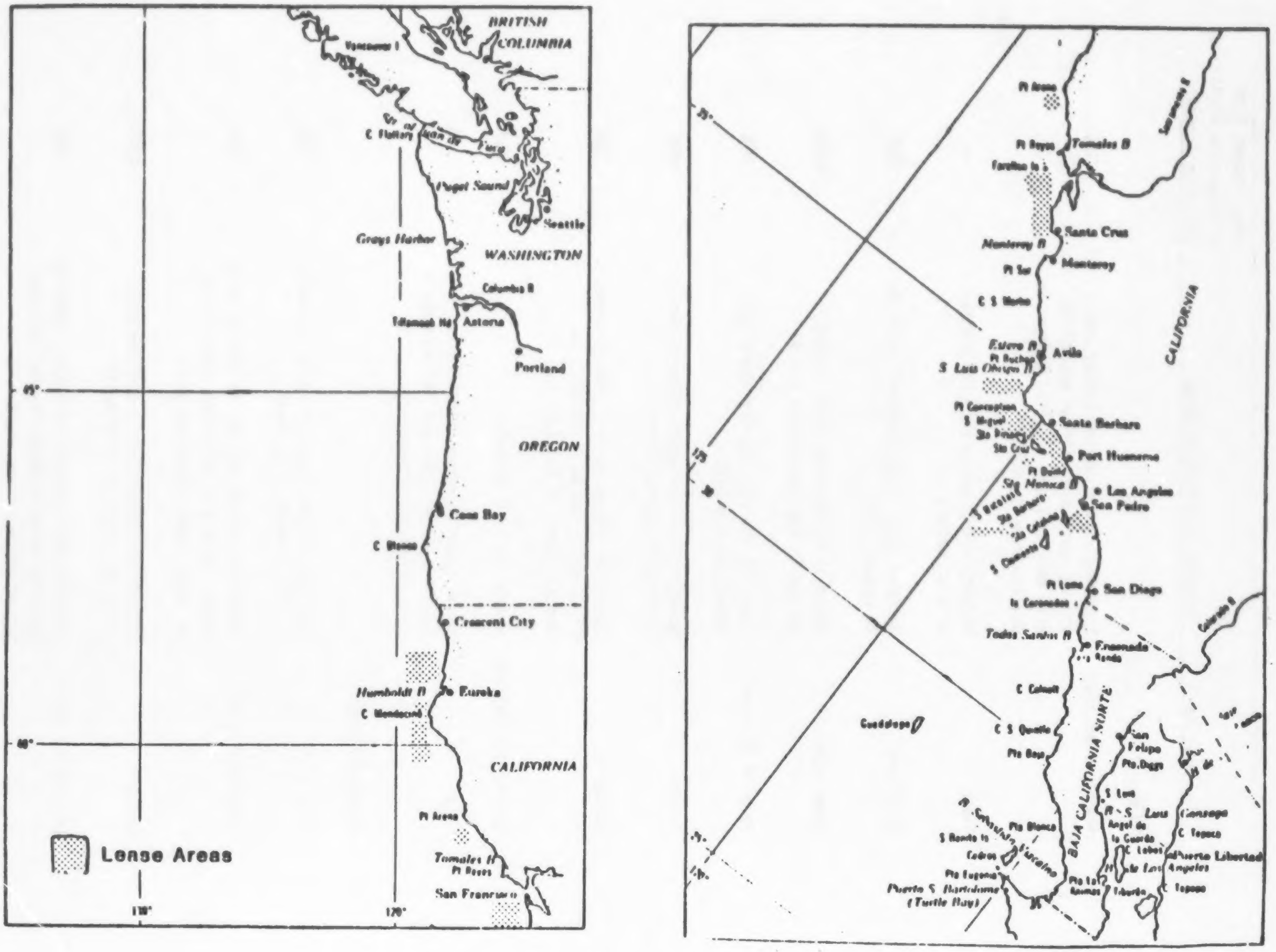


FIGURE 6-6 CALIFORNIA COASTLINE

TABLE 6-7 SPAWNING AND NURSERY AREAS FOR MAJOR COMMERCIAL FISH AND INVERTEBRATE SPECIES IN CENTRAL AND SOUTHERN CALIFORNIA

Species	Reproductive/Nursery area	Approximate % of nursery area within the 50 m isobath
Fish		
Northern anchovy	Spawning occurs during winter and spring nearshore; larvae associate with mackerel and rockfish larvae in shallow waters (<30m)	80%
Tuna	Nursery areas not within California or U.S. waters	—
Rockfish	Nursery areas from tidepool level to 30 meters deep	100%
Jack mackerel	Found in association with rockfish larvae in shallow waters (30m)	100%
Pacific herring	Spawning and rearing nearshore and estuaries and bays	90%
Salmon	Spawning in freshwater rivers; early nursery areas nearshore	100%
Sablefish	Juveniles found in less than 91 meters of water in summer; migrates to deeper water in the fall	50%
California halibut	Spawns in 5 to 18 meters	100%
Sole	Known spawning areas offshore in 55-549 m water; pelagic larvae remain many miles offshore	0%
Invertebrates		
Rock crab	Inshore species, particularly in rocky areas; inshore of 55 meters	90%
Dungeness crab	Greatest concentrations in two to 35 m water; bays and estuaries significant nursery areas first two years	100%
Abalone	Reared and harvested in shallow water areas of seven to 50 m depth	100%
Opalescant squid	Schools move inshore to spawn; Monterey Bay and Santa Barbara Channel Islands important spawning areas	80%

Table 6-8 lists these areas for southern and central California. Figure 6-7 shows the location of most of these areas in central California.

A zone enclosed by a 50 meter isobath will enclose the nursery areas for most commercially important species, the intertidal shorelines of offshore islands, and the areas of biological concern. For the most part, the 50 meter isobath falls within the state waters of California, occurring approximately one to two miles off the coast. In some areas, it extends beyond state waters.

TABLE 6-8
AREAS OF SPECIAL BIOLOGICAL SIGNIFICANCE (ASBS), ECOLOGICAL RESERVES/REFUGES, AND FEDERAL ESTUARINE SANCTUARIES IN CENTRAL AND SOUTHERN CALIFORNIA

Central California

Areas of Special Biological Significance (ASBS):

1. Farallon Island
2. Pt. Reyes Headland Reserve
3. Bird Rock
4. Double Point
5. Duxbury Reef Reserve
6. James V. Fitzgerald Marine Reserve
7. Ano Nuevo P. and Island
8. Pacific Grove Marine Gardens Fish Refuge and Hopkins Marine Life
9. Carmel Bay
10. Pt. Lobos Ecological Reserve
11. Julia Pfeiffer Burns Underwater Park

Ecological Reserves/Reserves:

1. Point Reyes Headland Reserve
2. Duxbury Reef Reserve
3. James V. Fitzgerald Marine Reserve
4. Point Lobos Ecological Reserve
5. Estero de Limantour Reserve
6. Morro Rock Ecological Reserve
7. Pismo Beach Ecological Reserve

Marine Life Refuges:

1. Pacific Grove Marine Gardens Fish Refuge
2. Hopkins Marine Life Refuge
3. California Sea Otter Refuge

Federal Estuarine Sanctuary:

1. Elkhorn Slough

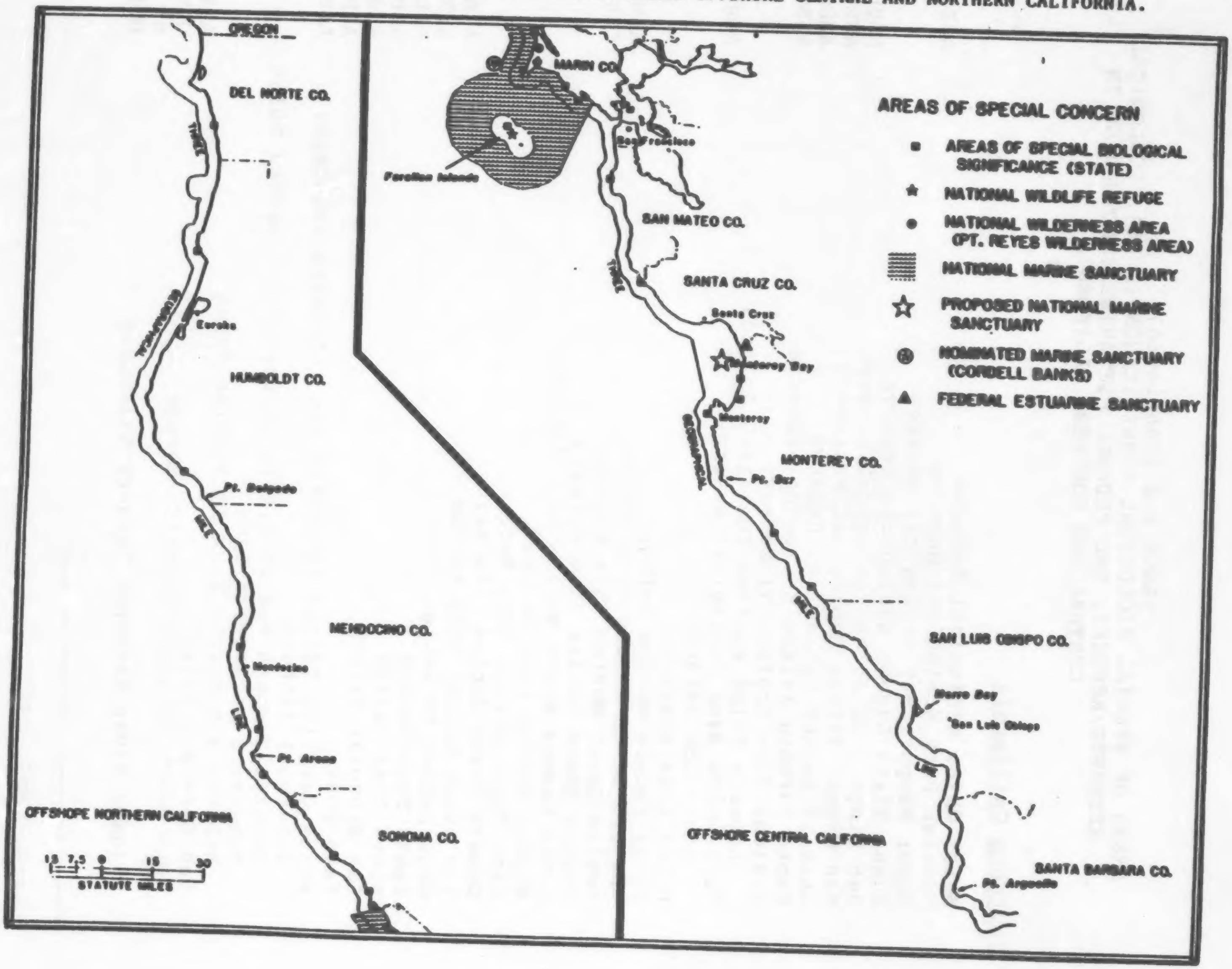
TABLE 6-8 (Continued)
AREAS OF SPECIAL BIOLOGICAL SIGNIFICANCE (ASBS), ECOLOGICAL RESERVES/REFUGES, AND FEDERAL ESTUARINE SANCTUARIES IN CENTRAL AND SOUTHERN CALIFORNIA

Southern California

Bolsa Chica Ecological Reserve	
Heisler Park Ecological Reserve	ASBS
Upper Newport Bay Ecological Reserve	
Buena Vista Lagoon Ecological Reserve	
San Diego - La Jolla Ecological Reserve	ASBS
San Miguel Island Ecological Reserve	ASBS
Anacapa Island Ecological Reserve	ASBS
Santa Barbara Island Ecological Reserve	ASBS
Abalone Cove Ecological Reserve - Lover's Point Reserve (Catalina Island)	
Farnsworth Bank Ecological Reserve (Catalina Island)	ASBS
Point Loma Reserve	
Point Fermin Marine Refuge	
Newport Beach Marine Life Refuge	ASBS
Irvine Coast Marine Life Refuge	ASBS
Laguna Beach Marine Life Refuge	
South Laguna Beach Marine Life Refuge	
Niguel Marine Life Refuge	
Dana Point Marine Life Refuge	
Doheny Beach Marine Life Refuge	
San Diego Marine Life Refuge	ASBS
Mugu Lagoon to Latigo Point	ASBS
Santa Rosa Island	ASBS
Santa Cruz Island	ASBS
San Nicholas Island	ASBS
Begg Rock	ASBS
Santa Catalina Island including the following subareas:	ASBS
Subarea 1 Isthmus	
Subarea 2 North end of Little Harbor to Ben Weston Point	
Subarea 3 Farnsworth Bank	
Subarea 4 Binnacle Rock to Jewfish Point	
San Clemente Island	ASBS
Seal Beach National Wildlife Refuge	U.S. Dept. of Navy
Tijuana River National Estuary Sanctuary	NOAA

Source: MMS, 1983.

FIGURE 6-7 AREAS OF SPECIAL BIOLOGICAL SIGNIFICANCE OFFSHORE CENTRAL AND NORTHERN CALIFORNIA.



7.0 FINDINGS AND CONCLUSIONS

7.1 DRILLING FLUIDS AND CUTTINGS

The current status of assessments of the potential impacts of drilling fluids and cuttings is that their conclusions are, in general, marked by contradictions and/or are highly qualified. The scope and utility of these general conclusions are substantially reduced by these qualifications, which are too frequently overlooked. The following sections present those areas that are considered to be, by general consensus, of low concern and those areas that possess a significant potential for adverse environmental impacts.

7.1.1 Toxicity of Drilling Fluids

This review of the composition, chemistry, and toxicity of drilling fluids covers four major topic areas: (1) the toxicity of drilling muds; (2) the source of this toxicity; (3) the correlation between mud components and/or characteristics and toxicity; and (4) bioaccumulation. In these discussions, a broad definition of "toxicity" is used that includes not only chemically-mediated toxic effects, but also any other potential source of an adverse environmental effect caused by drilling muds (e.g., physical effects).

7.1.1.1 Toxicity

There is a general consensus that generic drilling muds with no added diesel oil or mineral oil have low acute, lethal toxicity. However, the industry has acknowledged that the use of diesel and/or mineral oils as lubricating and spotting agents, at relatively high levels (two to four percent), is necessary for efficient operations. The addition of even small amounts (one percent) of diesel oil or mineral oil to generic drilling muds cause them to become some 10- to 100-fold more toxic.

Nongeneric muds (i.e., those which are not shown in Table 2-1) can be much more toxic than generic muds. One series of industry-supplied nongeneric muds, contaminated with relatively small amounts of oil (0.01-0.9 percent), were from 10 to 340 times more toxic than similar nongeneric muds, with the exception of KCL polymer muds. The contribution of specialty additives versus that of diesel oil to the observed toxicity of these muds is not known. One of these nongeneric muds exhibited a 96-hour LC_{50} of 26 ppm, which is approximately of the same order of toxicity as that of a biocide, formaldehyde (25-31 ppm).

Also, drilling muds possess a high Biochemical Oxygen Demand (BOD) that is highly correlated to their toxicity. Because existing test protocols routinely require both pre-aeration of drilling mud test materials and aeration of test media, these test procedures may reduce substantially the measured toxicity of drilling muds by masking potential BOD effects.

7.1.1.2 Sources of Toxicity

There are three sources of potential adverse effects from drilling muds: toxics, physical effects (grain-size alterations, smothering, abrasion, and/or clogging), and oxygen demand. Existing studies have not been designed, and therefore cannot be used, to discriminate between contributions of physical and chemical components. This finding has been noted in other reviews (Petrazzuolo, 1983a; NRC, 1983). The correlation between BOD and toxicity is a recent finding of this review. Test protocols, however, are not designed to discriminate this effect from toxic or physical effects (indeed, as indicated above, protocols are designed to minimize this effect).

7.1.1.3 Correlations to Toxicity

Among drilling fluid components that have been examined, only diesel oil and mineral oil possess a high, statistically demonstrable correlation to observed toxicity. Biocides, although existing data are insufficient for any statistical analysis, are the only other group of components that can be anticipated to substantially contribute to toxicity. However, diesel and mineral oils, although correlated to toxicity, do not explain all of the observed toxicity of muds, especially for KCL polymer muds and lime muds.

Bulk metals content appears to have a low correlation to observed toxicity of drilling muds, with the possible exception of a weak correlation to chromium. The strong statistical correlation between toxicity and BOD, which is all the more surprising because of test designs that should have minimized BOD effects, should be investigated further.

7.1.1.4 Bioaccumulation

Laboratory studies have indicated that bioaccumulation has been observed for nearly all metals that have been studied, including barium, cadmium, chromium, lead, strontium, and zinc. Barium and chromium show the most dramatic increases (30- to 300-fold); others are much lower (2- to 25-fold). Data on mercury are conspicuous by their absence. However, bioaccumulation test procedures are characterized by design factors that seriously reduce the ability to quantify the bioaccumulation hazard of drilling muds.

Field data for either one-well operations or small drilling fluid discharges show that sediment levels were elevated for a variety of metals (barium, cadmium, chromium, lead, mercury, nickel, vanadium, and zinc) in a distance-dependent manner. Bioaccumulation was noted in field-collected organisms for several of these metals, although at relatively low levels (2- to 10-fold compared to organisms collected at reference stations). There are no laboratory or field data that are adequate to assess the bioaccumulation hazard of organic components of drilling fluids.

7.1.2 Field Assessments of Impacts from Drilling Activities

7.1.2.1 Studies of Impacts from Single Wells

Although a number of studies have been conducted around exploratory wells, the design of most of these studies was sufficient only to detect gross changes in benthic communities (i.e., changes of 100 percent or greater). Only two studies have been designed and performed that were capable of detecting changes at low to moderate levels (i.e., 25-50 percent).

One of these studies, conducted in a very high energy, dispersive environment (Georges Bank), indicated that no significant effects could be detected from single-well discharges. The inability to detect effects does not necessarily indicate a complete lack of impact, but that effects are dispersed to relatively low levels (< 25-50 percent), over a larger area, in a high energy situation.

The second of these studies was conducted in an open shelf area (Baltimore Canyon) of the mid-Atlantic, 160 km offshore, in a water depth of 120 m. The mid-Atlantic study showed effects to several hundred meters. These effects persisted at least one year after the discharges ceased. The complete areal extent of impact cannot be clearly delineated because of the lack of adequate reference stations. Also, some uncertainty exists as to whether the large overall change in benthic densities in the area was due to natural variation.

There is no study of impacts from a single-well drilling operation in a near-shore, shallow water situation that meets reasonable statistical and sampling design criteria.

7.1.2.2 Studies of Impacts from Multiple Wells

Multiple-well discharges are associated with intensive, local exploratory activities or development drilling. Several attempts to assess the effects of development and production activities after the fact have been made in the Gulf of Mexico. The studies are inconclusive because of problems in finding adequate historical or spatial reference sites and in determining the contribution of one factor (drilling mud discharges) in a large, complex, multifactorial system. Therefore, the studies of production facilities that have been conducted to date do not allow an adequate assessment of potential impacts that may result from multiple-well discharges of muds and cuttings. In addition, no study has been conducted to assess benthic impacts from a development operation.

7.1.2.3 Factors Contributing to Potential Impacts

Since existing studies only cover a very limited range of drilling scenarios, this section will discuss some of the factors that would contribute to situations of increased risk from the discharge of muds and cuttings. Such increased risks may be due to the nature or quantities of discharged materials, the physical characteristics of the receiving water, or the biological or usage characteristics of the receiving water.

- Development Activities

  The potential effects from development activities (as opposed to exploratory activities) are due to the quantities and nature of the materials discharged. Greatly increased quantities of material are discharged during development (typically, 24-60 wells per platform) compared to a single-well operation. Also, the general trend has been toward fewer platforms with more wells per platform. This trend results in greater directional drilling, which is much more likely to require the use of lubricating and spotting oils than straight-hole exploratory drilling. Consequently, the muds used in directional development drilling are likely to be among the more toxic muds discharged.

- Shallow and/or Poorly Flushed Coastal Waters

  The areas where drilling fluids are most likely to cause detectable problems associated with water column toxicity are those with shallow water (i.e., where dispersion is limited) or poorly flushed/low energy areas (i.e., where the amount of muds discharged is large compared to local water flux). Sediment toxicity to benthic organisms, oxygen depletion effects, and physical effects due to deposition also are most likely to be observed in these areas.

  Any effects due to oxygen depletion should be of short duration, approximately six months to one year. The persistence of physical effects and sediment toxicity is not known, although in one low energy environment (the Mid-Atlantic) partial recovery occurred within one year. Barite, clays, and polynuclear aromatic hydrocarbons are fairly persistent components of drilling muds, and complete recovery may take a long time in shallow and/or poorly flushed areas.

- Areas Subjected to Other Sources of Pollution and/or Episodic Stress

  If an ecological system is already subjected to large and varied contaminant inputs, adding further contaminants may cause significant problems, even if the additional load is comparatively small. For example, the BOD loadings described in Section 2 could contribute significantly to water quality degradation in areas such as Louisiana state waters, which are (1) shallow, (2) subject to high levels of drilling activity, (3) also subject to high levels of other contaminant inputs (i.e., via the Mississippi River), and (4) subject to episodic anoxic events of unknown cause.

Areas that are subject to higher loadings from other sources of pollution tend to be the nearshore coastal areas, which are also often shallow, poorly flushed areas. In addition, the usage of near-shore coastal areas for recreation and commercial fishing is characteristically high, which is yet another reason for concern in assessing potential impacts from these discharges.

- Communities Ill-Adapted to Sedimentation Effects

Certain communities are not well-adapted to stresses associated with sedimentation effects. These communities generally are represented by clear-water, hard-bottom communities. Examples would include coral reefs, macrophyte beds, and "live-bottom" areas as designated by the Minerals Management Service.

- Shellfisheries

Because of several factors, shellfisheries represent potentially high areas of environmental impact. In areas that may be subject to deposition or transport of drilling muds from intensive drilling activities, shellfisheries are a concern because: (1) there are very limited data on sediment contaminant enrichment; (2) several potential contaminants (metals and organics) are highly persistent; (3) bioaccumulation data qualitatively indicate a potential hazard, but are insufficient to quantify the hazard from drilling muds; and (4) the capacity of this group of animals to accumulate such materials to exceptionally high levels is well documented for both metals and organics. This concern, therefore, is primarily based on the lack of data adequate to quantify the potential effect.

7.2 PRODUCED WATER

7.2.1 Toxicity of Produced Water

Data presented in this review lead to the following conclusions concerning the toxicity of produced water: (1) the acute lethal toxicity of produced water that does not contain biocides or other toxic chemical additives is low; (2) the acute lethal toxicity of produced water is greatly increased when biocides or other toxic chemical additives are present; and (3) chronic toxicity of produced water is suggested by existing data and must be investigated further.

There is very limited information on the toxicity of produced water. Several acute lethal toxicity studies were conducted at one platform in the Gulf of Mexico. Results from these studies are consistent with the above conclusions. When biocides were present, and had not been scavenged, the acute lethal toxicity of produced water was substantially greater than when biocides either were not present, or had been scavenged.

However, Middleditch (1984) noted that such scavenging reactions are reversible. Thus, even though measurable biocides may not be detected in the effluent, they could be released after discharge. This possibility may explain why divers working near the discharge of this particular platform, at which acrolein was used as a biocide and was scavenged prior to discharge, complained of eye and skin irritations, which at times caused divers to discontinue their activities temporarily. At present, there is very little information on the extent of biocide or other chemical additive usage, the concentrations of these chemicals in produced water discharges, or the resultant toxic effects of these additives.

In the absence of biocides or other toxic additives, the acute lethal toxicity of produced water appears to be reduced and is probably related, in part, to the presence of lighter aromatic hydrocarbons (benzene through naphthalene). The toxicity tests conducted on produced water were performed in a manner that would have resulted in loss of at least a portion of these toxic volatile organics. Thus, these tests probably underestimate acute lethal toxicity somewhat. Unfortunately, no measurements were made of these compounds at any time during the toxicity tests.

There is even less information on the chronic toxicity of produced waters. Studies done in the North Sea have indicated that produced water can exert chronic effects on plankton at diluted concentrations. The limited information suggests that chronic effects from produced water discharges could be important, at least in certain areas.

Because produced water discharges provide a continual input of low levels of petroleum hydrocarbons and chemical additives, there is the possibility of an accumulation in the water column. Such an accumulation is most likely to occur in areas of limited flushing. However, even at the high energy Buccaneer Field site, elevated concentrations of volatile liquid hydrocarbons were observed several kilometers from the platform, despite a comparatively small produced water discharge volume (600 bbl/day).

These elevated concentrations were above those that Sauer (1980) identified as indicative of anthropogenically influenced coastal waters of the Gulf of Mexico. Middleditch (1984) and Sauer (1980) noted that while these low concentrations of aromatic hydrocarbons (on the order of a few ppb) are well below levels needed to cause mortalities, they are comparable to levels reported as being responsible for behavioral changes (i.e., sublethal effects).

There is clear evidence that the hydrocarbons, and possibly additives, that are present in produced water discharges can exert chronic effects on benthic organisms around production platforms. This was apparent both in the shallow water (2.5 m) Trinity Bay study, where elevated concentrations of total naphthalenes were observed in the sediments, but also in the deeper water (20 m) Buccaneer Field site. The full areal extent of chronic effects of produced water discharges on the benthos is difficult to delineate. This difficulty is due to the generally elevated levels of hydrocarbons and other chemicals in sediments over wide areas in the Gulf of Mexico.

This creates generalized contamination "signal to noise" problems with respect to detecting effects of individual discharges. Any field study probably would show, at best, measurable localized effects. Beyond that, the influence of discharges on the benthos could be integrated with other influences (e.g., other platforms, riverine inputs, etc.) and could not be clearly delineated. Simply because measurable effects are observed near individual platforms does not imply that effects are locally restricted.

7.2.2 Comparison with Other Assessments

Two assessments of the environmental implications of produced water discharges include a recent report by Middleditch (1984) for the American Petroleum Institute (API) and a review by Menzie (1982). These assessments used an information base that was generally the same as that utilized in this report. These two earlier assessments agree with this report on most technical points. Disagreements occur mainly in the significance attached to the observed effects. These differences arise, in part, from the considerable uncertainty that exists concerning environmental effects of produced water discharges. For example, the API report prepared by Middleditch (1984) concludes that "at the current time, we are unable to claim that effects of produced water discharges have been fully delineated."

The Middleditch report also concludes that produced water effects are probably minor and limited to a relatively small area. Middleditch acknowledges that both the scientific and local communities would find data more convincing if they were adequate to define the maximum extent of specific effects. However, as noted above, this effort is generally not possible from field studies because effects from individual platforms become integrated with other generalized influences beyond the immediate vicinity of the platform (e.g., beyond a few hundred meters), and are extremely difficult to sort out.

Reviews, including that of Middleditch (1984), have attempted to place various sources of petroleum hydrocarbons in perspective through comparisons with other sources (river discharge, tankers, oil seeps). Generally, such comparisons show that produced water discharges contribute a comparatively small percentage of the overall input on a Gulf-wide, ocean-wide, or world-wide basis. This type of comparison is often used to establish "significance." Thus, it is argued that produced water discharges are not significant. However, simply because the relative contribution is small, it does not follow that produced water discharges are insignificant. First, the collective sum of numerous small dischargers may not represent a small contribution on a regional level. Second, discharges of produced water can exert environmental effects locally, as indicated by the data presented earlier.

Middleditch (1984) and Menzie (1982) both note Sauer's (1980) observation that the coastal Gulf of Mexico already exhibits elevated levels of volatile liquid hydrocarbons and that existing concentrations are in the range that could result in sublethal effects. Menzie (1982) suggests the possibility that a build-up of hydrocarbons in the water column is possible in areas of limited flushing (e.g., coastal embayments). Both reviewers acknowledge that effects of produced water discharges are more likely to occur in shallow coastal areas than in deeper offshore areas. However, neither report discusses this effect in terms of a particular depth or area.

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APPENDIX A

SUPPLEMENTARY INFORMATION ON FIELD STUDIES

A. SUPPLEMENTAL INFORMATION ON FIELD STUDIES

The exploration for and production of offshore oil and gas sometimes brings into conflict the demand for energy and the need for environmental protection. In areas of particularly valuable ecologic resources, interest in these issues may run high. Three locations of recent exploration in or near biologically sensitive areas are presented below: the Flower Garden Banks (Gulf of Mexico), Georges Bank (North Atlantic), and Norton Sound (Alaska). These brief case studies illustrate the numerous issues involved in the controversy surrounding offshore oil and gas development.

A.1 THE FLOWER GARDEN BANKS

The Flower Garden Banks are the only true coral reefs in the northwestern Gulf of Mexico and are located approximately 200 km (120 mi) off the coast of Galveston, Texas. There are two major reefs, known as the East and West Banks, which occupy approximately 28 and 40 hectares (69 and 99 acres), respectively. The uniqueness of the reefs in this area affords them special scientific and ecological interest. The area surrounding the banks is presently being explored for oil and gas deposits, and there is concern that this and future drilling may have adverse impacts on the health of the ecological community in general and the corals in particular. The material in this section draws heavily on the Draft Phase 3 Report, Effects of Drilling Muds on the Flower Garden Banks Coral Reefs, prepared by Clement Associates, Inc., (1983) as part of a settlement agreement regarding drilling in the area.

A.1.1 Biota

The predominant coral species on the East and West Flower Garden reefs are *Montastrea annularis*, *Diploria strigosa*, *Colpophyllia natans*, *Porites astreoides*, *Montastrea cavernosa*, and *Millepora* sp. (Gettleson, 1978). Smaller populations of *Madracis decatis*, *Mussa anulosa*, and *Agaricia* sp. have also been noted. The major differences between biota of the two banks are areas of *Madracis mirabilis* and leafy algae found only at the East Bank (Bright 1977, reported in Clements 1983).

Corals are the organisms of greatest concern in the area, although there are also other important biota present. The corals generally extend to no more than 55 m (180 ft) in depth. Below the coral, at depths of 50 to 80 m (164 to 263 ft), the predominant organisms are red coraline algae, which secrete calcium carbonate and contribute to the structure of the reef. Depths of 60 to 100 m (197 to 329 ft) constitute the transition zone from shallow to deep water, and are inhabited by antipatharian organisms. Antipatharians physically resemble sea whips and can grow as long as 1.8 to 3 m (6 to 10 ft). Various reef fish also inhabit this level. Significant impacts on these deeper water organisms could affect the entire reef ecosystem.

Corals are organisms which are sensitive to changes in their environmental conditions. The Flower Gardens are thought to be particularly vulnerable to stress for several reasons (Clement, 1983):

(1) They are near the lower limit of the temperature range tolerated by reef-building corals.

(2) They contain a limited variety of species.

(3) They are physically isolated from other coral reefs which could provide for recolonization if needed.

(4) There is empirical evidence that growth patterns for one of the dominant species are correlated with water temperatures and may also be affected by fluctuations in discharge from the Mississippi and Atchafalaya Rivers (Dodge and Lang, 1982).

(5) They are in a zone frequently affected by severe hurricanes.

A.1.1.1 Impacts from Drilling Activity

Adverse effects on corals, if they occur, could be the result of increased turbidity, decreased available sunlight, or toxic effects from metals or organic compounds in drilling fluids. The major potential threat is believed to be associated with turbidity and possible burial from drilling fluid discharges.

There are few monitoring projects from the Banks. The most extensive information available, collected under the direction of the Minerals Management Service, includes topographic features, geology, biological monitoring, water and sediment dynamics, and hydrocarbon and carbon analyses. A final synthesis report should be released in the near future. Other biological monitoring and physical dispersion studies are also in progress (Clements, 1983). Numerous controlled experiments with corals have been conducted and are discussed in Section 4 of this report (Thompson and Bright, 1980; Hudson and Robin, 1980). These experiments verify the sensitivity of corals to drilling muds.

At French Frigate Shoals, Hawaii, coral reefs were able to withstand a spill of 2,200 metric tons (2,426 tons) of kaolin clay without extensive damage (Neff, 1980). Within 50 m of the wreck some corals were smothered, and Pocillopora spp. were bleached because of the lack of light, but survived. Beyond a 50 m (164 ft) radius, no effects to the corals were observed. Exploratory drilling in a coral reef off Palawan Island in the Philippines produced an estimated 70-90 percent reduction of some coral species (Hudson et al., 1982). The affected area formed an ellipse 115 m by 85 m extending out from the well-heads so coral mortalities were presumed to be caused by smothering or toxic effects from discharged mud and cuttings.

A.1.1.2 Administrative Context

Several Federal agencies have responsibilities for various aspects of the Flower Garden Banks. The Minerals Management Service (formerly the Bureau of Land Management) administers the leasing program. EPA, through the NPDES permitting process, has responsibility for regulating discharges in the area.

In order to resolve the conflicts regarding the environmental acceptability of drilling in the area, in 1981 the EPA, Natural Resources Defence Council, Sierra Club, and the interested oil companies entered into agreements regarding the conduct of drilling. The agreements permitted the discharge of water-based drilling fluids with certain restrictions and required completion of monitoring studies and other research by the oil companies. Monitoring will be conducted for: (1) hydrocarbons, barium, and chromium in sediments, (2) barium metals, and hydrocarbons in drilling fluids, and (3) possible barium and chromium accumulation in a representative bivalue.

Transect measurements, growth/regression measurements, and larval recolonization will also be evaluated at the East Flower Garden Bank. The monitoring of exploratory wells will continue for six months after the end of drilling. Other oil companies are funding a review of the existing scientific literature to assess the potential adverse effects of drilling fluids on the Flower Garden Banks (i.e., the Clements, Inc. report).

The mutual agreements stipulate conditions that will apply to all drilling in the area. Drilling is not allowed on the banks themselves, and discharges must be a minimum of 1,000 m (3,280 ft) from the 100 m (328 ft) isobath (depth) line. All discharges within 5,500 m of the 100 m isobath line must be diluted with seawater until discharge concentration is reduced at lease one order of magnitude. Diesel oil is not permitted in fluids discharged in the area. Finally, all discharges from drilling platforms must be shunted to a point approximately 10 m (33 ft) from the bottom, releasing this material below the thermocline. This practice should confine the discharged material to an area near the sea bottom. Initial data indicate that the shunting regulations are effective (Gettleson, 1978; and McGrail et al., 1982, reported in Clements, 1983). While typical conditions in the area may keep these shunted discharges near the bottom, such a conclusion must be accepted with caution. Many factors affecting ocean transport of pollutants are poorly understood.

Monitoring of water quality, infaunal benthic, and nektonic organisms is being conducted for the EPA by the National Marine Fisheries Service. Underwater video systems are being used to census fish populations at different sites and depths. Major nektonic fish include creole fish, porgies, red snapper, grouper, and other reef fish. Monitoring efforts under this program began with an initial cruise in October, 1980 and are being focused in the vicinity of the Mobil production platform.

A.1.2 Recent Drilling Activity

Drilling began in the Flower Garden Banks area in 1973. At least one production platform is in place in the Flower Garden Banks area, installed by the Mobil Oil Corporation in the fall of 1981. The platform is approximately 1.5 miles (2,500 m) from the East Flower Garden Banks, and is projected to operate eight production wells.

Approximately six exploratory wells have been drilled near both the East and West Banks. Companies active in the area include Mobil, Union Oil, American Natural Resources (formerly American Natural Gas), Pennzoil, and Anadarko. Early results from the work of Meyer (1981), Trefry et al., (1981), and Trocine and Trefry (1982) of measured sediment accumulations of barium, chromium, iron, and other trace metals contained in drilling fluids, and found no evidence of trace metal pollution from drilling activity in the area, except for barium. Cuttings piles in the area have been observed within 10 to 50 m of the point of discharge. Elevated barium levels have been observed out to 500 m from discharges, and drop to background levels within 300 to 1,000 m (Clements, 1983). The Clements report concludes that the two most likely causes of significant environmental effects are (1) burial and other effects to benthos in the near vicinity of the discharge, and (2) exposure in the event of a blowout, should one occur. Both scenarios are considered unlikely, as are other types of exposures, leading to their conclusion that the overall risk to the reef ecosystem from drilling is minimal. There are, however, many shortcomings in the current information base for assessing potential impacts, which severely limits the ability to detect impacts, should they be occurring. Thus, the initial indications of minimal adverse environmental effects should be accepted with caution.

A.2 GEORGES BANK

The Georges Bank area is located approximately 300 km (180 mi) southeast of Cape Cod, Massachusetts. The area is situated on the outer continental shelf, approximately 200 km (120 mi) landward from the closest point of approach of the Gulf Stream. Georges Bank has been described as one of the richest spawning and fishing grounds in the world (Houghton et al., 1981). The controversy surrounding drilling here centers on whether the search for oil and gas will have a damaging effect on the vital fishing stocks of the area, and how these uses might be compatibly maintained. Houghton et al., (1981) prepared a study of the "Fate and Effects of Drilling Fluids and Cuttings at Georges Bank" for the Bureau of Land Management, which provided substantial data for this section.

A.2.1 Physical Setting

The hydrodynamic regime of Georges Bank is a high energy one. Tracts already leased for drilling (Lease Sale No. 42) are from 50 to 100 m (164 to 329 ft) deep; depths in tracts scheduled for future leasing range from 100 to 2,000 m (328 to 6,562 ft). Summer thermal stratification is distinct, while in winter the water temperatures are relatively uniform. Seasonal salinity variations are less extreme than temperature variations; however, spring runoff from the continent does result in some dilution of the upper water layers.

Flow patterns are complex. A mean clockwise gyre exists over Georges Bank, while a counterclockwise flow pattern predominates just to the north in the Gulf of Maine. The gyre over Georges Bank appears to be strongest in the spring and has an intermittently closed circulation with potential for recirculating discharges, although considerable variability is present in circulation patterns. Current meter readings near the surface reveal a mean drift of approximately 25 to 30 cm/sec (0.82 to 0.98 ft/sec) in the northern part of the Bank, and 5 to 10 cm/sec (0.164 to 0.33 ft/sec) in the southern part. At greater depths, current speeds decrease.

Four potential surface and sub-surface exits from the overall circulatory system have been identified. One is to the northwest and empties into the Gulf of Maine, which has been identified as an area of potential accumulation of drilling fluids. Other potential exits have been identified to the northeast, south, and southwest. Recent research confirms that the "Mud Patch" area (to the southwest of the Bank) is a sink for fine-grained sediments and a potential sink for sediment related pollutants (Bothner et al., 1981). While deposited material may be subsequently removed from the Mud Patch to the southwest, sediment inputs were found to exceed losses.

Georges Bank is located at the convergence of the southerly flowing Labrador Current and the northerly flowing Gulf Stream, which together drive the complex circulation and promote upwelling. Vertical mixing of the water column is good, driven by the influence of winds and currents in this shallow area (Houghton et al., 1981). Fine sediments do not accumulate much because of high current speeds and frequent resuspension. Storms passing through this area can be severe, particularly during the winter months, contributing to the dispersal of sediments.

The Georges Bank bottom sediment is composed primarily of medium and fine sand, with patches of gravel, and small areas of silt and clay. The presence of these four sediment types promotes biological richness and diversity. Significant quantities of mollusk shell fragments are present. More detailed information on the Georges Bank physical environment can be found in the Environmental Impact Statement for Lease Sale No. 52 (BLM, 1982).

The ambient water column is contaminated with hydrocarbons, presumably due to frequent marine discharges such as tanker ballast discharge (BLM, 1977). The most severe oil spill to occur in the area was the wreck of the oil tanker Argo Merchant off Nantucket Island in 1976, which spilled nearly eight million gallons of fuel oil.

A.2.2 The Georges Bank Fishery

The richness of the Georges Bank fishery has been attributed to a combination of several factors (Houghton et al., 1981), namely:

- The location of Georges Bank near the convergence of the Labrador Current and the Gulf Stream, which results in the upwelling of nutrient-laden bottom waters.

- Continuous vertical mixing of waters over the Bank due to its shallowness and the influence of wind and currents.

- The high levels of mixing and nutrients which support a rich pelagic food chain including phytoplankton, zooplankton, and other nekton.

- The high benthic diversity due to various types of surficial sediments.

- Productive benthic macroinvertebrate populations over some parts of the bank which are correlated with high bottom fish production.

Species which use Georges Bank extensively for spawning include hake, herring, flounder, plaice, butterfish, cusk, rockling, cunner, sculpin, and sand lance (Colten et al., 1979, as in Houghton et al., 1981). Shellfish also comprise an important economic resource on the bank, particularly sea scallops and lobster. Shellfish of lesser importance include surf clam, ocean quahog, and red crab.

A.2.3 Potential Impacts from Drilling Activity

Sea scallops (Placopecten magellanicus) are among the organisms of greatest concern with regard to drilling fluid and cuttings impacts because of their commercial importance and potential for accumulations of fine solids or trace metals. Laboratory studies reveal accumulations of barium and chromium in the kidneys of sea scallops after exposure to high concentrations of ferrochrome lignosulfonate drilling fluid (Liss et al., 1980). However, the edible part of the scallop, the adductor muscle, did not show similar accumulation. Sea scallops are found primarily at depths of 40 to 100 m (131 to 328 ft) on firm sand or gravel bottoms. During the period from 1961 to 1973, the scallop catch declined from a high of 10,900 kg (24,000 lbs) to a low of only 1,800 kg (4,000) lbs. Houghton et al., (1981) report that the stock has shown recovery in recent years, as the Canadian fleet reported record catches in 1977 through 1979, but the scallop fishery has since shown a major decline.

The lobster fishery appears to have reached its peak approximately 20 years ago. Declining catches have resulted in fishing efforts moving out further from the coast. It is known that lobsters are sensitive to environmental changes, and sensitivity to drilling fluids has been shown in laboratory tests (see Section 4).

Potential impacts of future drilling fluid accumulations on the lobster community are unknown. Lobsters breed in shallow coastal waters, and spend the rest of the year in the canyon heads on the deeper areas of Georges Bank. Impacts could occur either in the shallow breeding areas or in the canyon heads if drilling materials are transported from platform proximities to deeper waters by way of submarine canyons (Dr. Eng, EPA Region I, to T. Mors, Dalton'Dalton'Newport, personal communication, 1982).

Dispersion of the upper plume of drilling fluid discharges in this area is expected to be rapid. Houghton et. al (1981) estimate a dilution of 500 to 1,000:1 within a few meters of the discharge, increasing to 10,000:1 within 100 or 200 m (328 or 656 ft). This might result in ambient concentrations in the zone up to 100 m (328 ft) to be greater than the 96-hour LC_{50} concentration level for the most sensitive species and the most toxic muds (i.e., LC_{50} of 100 ppm). Serious effects to nektonic organisms would be expected, however, only if they maintain themselves within the plume near the platform for long periods. Chronic impacts could be experienced by organisms remaining very near the plume formed by the shale shaker because of the semi-continuous nature of this discharge. Planktonic organisms may be killed if entrained in the plume, particularly during the sensitive molting period.

Benthic accumulations of fine solids are not expected to persist in the Georges Bank area because wind and tidal turbulence in the shallow waters removes deposited material rapidly. Fine materials can eventually be transported out of the Georges Bank area to depositional sinks such as the Gulf of Maine. In such sinks, minimal impact is anticipated because of dilution of drilling discharges with other accumulated solids, and adaptation of organisms to the fine-grained sediments (Houghton et al., 1981). However, the initial cuttings pile formation can impact the benthic community in highly localized areas through burial.

Houghton et al., (1981) conducted a worst case environmental assessment for exploratory and development scenarios in the Georges Bank area. They estimated the effect of drilling mud discharges were spread evenly within a 3,218 m (2 mi) radius of a well, and mixed to depths of 1 cm and 5 cm (Table A-1). In the short-term scenarios (1 cm deep mixing), drilling fluid discharges could be responsible for increases in sediment concentrations of mud solids, barium (505 percent), chromium (26 percent), nickel (3 percent), lead (1 percent) and

TABLE A-1

INCREMENTAL CONCENTRATION OF MUD SOLIDS AND METALS IN TOP 1 AND 5 CM OF BOTTOM SEDIMENTS WITHIN 2-MILE (3,218 m) RADIUS OF WELL COMPARED TO AMBIENT METALS CONCENTRATIONS [a]

Mud Component	Total Amount Discharged (kg)	Concentration (mg/kg)[b] 1 cm	5 cm	Ambient Concentration (mg/kg)
Mud Solids	627,500	1,205	241	-
Ba	305,175	586	117	116 (< 44 - 290)
Cr	964	1.9	0.4	7.2 (2.2 - 27)
Cd	< 4	0.008	0.002	1.3 (1.0 - 20)
Pb	23	0.044	0.009	4.2 (1.4 - 96)
Hg	< 4	0.008	0.002	-
Ni	39	0.08	0.02	2.4 (1.2 - 13)
V	41	0.08	0.02	11.5 (10 - 34)
Zn	332	0.6	0.1	5.2 (1.2 - 50)

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[a] Even spreading within, and zero transport beyond, 3,218 m is assumed.

[b] Data from ERCO, 1980: median and range for totally digested samples from Stations 9, 12, 13, 18, 20, 21, 23, 25, 26, 28, and 29 in general vicinity of lease area.

Table reproduced without alteration from Houghton et al., (1981).

zinc (11.5 percent) compared with background levels. In the long-term scenario (5 cm deep mixing), the increase over background concentration appears insignificant except for barium (100 percent), chromium (5.5 percent), and zinc (2 percent).

The researchers also estimated bottom area affected by drilling fluid and cuttings discharges from a high development scenario (28 platforms, 420 wells). To estimate the extent of effects caused by multiple wells, they assumed a radius of accumulation 110 percent that of a single well for five or more wells from a single platform. Given these assumptions, only 0.2 percent (127 km^2 or 31,382 acres) of the Georges Bank bottom area would be affected by drilling activity. This would impact benthic organisms inhabiting the area near the discharges, but should not seriously disrupt fish stocks which depend on benthic organisms as a major source of food.

Finally, the researchers speculated on what might occur if discharged drilling fluids became trapped in the Georges Bank gyre. Assuming all fluids from one year were retained and evenly distributed throughout the gyre, they found that resultant pollutant levels would not be significantly greater than baseline levels. Resultant concentrations would be 0.023 mg/l of mud solids fluids, 0.01 μg/l of barium, 0.04 μg/l of Cr, and 0.15 μg/l of Zn. In actuality, some of the discharged material would be transported out of the gyre by the circulatory patterns.

Bothner et al., (1982) found post-drilling barium concentrations in unfractionated sediments increased by 350 percent 200 m from one drill site and by 230 percent at a second. Elevated concentrations were observable at a distance of 6 km from the rig. The authors estimated that, overall, approxi- mately 18 percent of the barite discharged from the second rig was contained in sediments within a 6 km radius, based on samples taken one month before the end of drilling. No changes in the concentrations of chromium or other metals in sediments were observed which could be attributed to drilling activity.

A.2.4 Administrative Context

To date only Lease Sale No. 42 in the Georges Bank area has been completed. The sale was held in December 1979, and the first drilling activity began in July 1981. Shell, Mobil, Tenneco, and Conoco are involved; Exxon was involved, but has since withdrawn from the area. Approximately eight exploratory wells have been drilled with no hydrocarbon discovery, and no further drilling is slated for the immediate future. A Final Environmental Impact Statement for Lease Sale No. 52 was published in April 1982 by the Bureau of Land Management (BLM, 1982). The area involved has since been modified and a new sale is scheduled for the fall of 1984.

NPDES permits for drillers in the North Atlantic area require shunting of all discharges to the "lowest point achievable," which in practice would be 15 to 25 m (49 to 82 ft) below the surface. The intent of this requirement is to limit adverse effects to pelagic eggs and larvae by confining discharges to below the pycnocline. In Georges Bank, the discharge pipes may not be below the pycnocline. No studies to date have assessed the effectiveness of this technique in achieving its intended objective.

Permits further stipulate that only water-based drilling fluids may be discharged. These fluids must be one of the standard EPA generic formulations; if a non-standard mud or constituent is used, it must be approved by EPA for ocean discharge. Mud samples must be taken and analyzed for each 305 m (1,000 ft) of drilling which occurs.

In order to ensure the continued integrity of the Georges Bank ecology, a Biological Task Force (BTF) including members of MMS, FWS, USGS, EPA, and NOAA, and with the consultation of the affected coastal states, was created to make recommendations on monitoring activities. Monitoring operations were initiated in 1981 based on the recommendations of the BTF. The monitoring program focused primarily on the chemistry and quality of sediments and on effects to the benthic community. Potential impacts to nectonic and planktonic organisms from drilling fluid concentrations were judged by the BTF to be unlikely. Thirteen "regional stations" were located to identify long-term sediment changes caused by oil and gas activities. The regional stations have monitored sediment pollution and sample benthic epifauna and infauna. In addition, intensive sampling using 29 site-specific stations took place within close range (5 km or 3 mi) of an active exploratory drilling rig. Sampling at these sites will continue for the duration of the leasing period. The first research cruise of the program took place in July of 1981 and four cruises have been completed through 1982. Cruises were scheduled to provide a preliminary evaluation of seasonal environmental variations. There was some detrimental effect to the benthic community; however, it was determined that severe winter storms in February 1982 were responsible for resuspension of sediments which apparently lessened the effects of drilling discharges (NRC, 1983).

A.3 NORTON SOUND

Norton Sound, the site of proposed oil and gas Lease Sale No. 57, is located in the northeastern Bering Sea off the western coast of Alaska. The proposed lease area includes 429 blocks covering 2.4 million acres, or 29 percent of the total Norton Sound area. Offshore distances range from 14.4 to 99.2 km (8.6 to 60 mi) and are closest to shore in the Yukon Delta Region (BLM, 1982). Norton Sound can be divided into three regions, each with its own unique flora, fauna, and ecological vulnerabilities:

- Yukon Delta region - a complex estuarine system which includes the Clarence Rhodes National Wildlife Refuge.
- Inner Norton Sound - the warmer, shallow Alaskan coastal waters east of 163^{o}W longitude.
- Outer Norton Sound - the colder, deeper, more saline waters overlying the Bering Sea shelf west of 163^{o}W longitude.

Norton Sound lies along major migration routes for many species of marine mammals and birds. The Yukon Delta region, coastal bluffs, and rocky islands located in Norton Sound are important nesting and foraging grounds for hundreds of species of seabirds, shorebirds, and waterfowl. Marine animals found in the Norton Sound area over the course of a year include five endangered whale species and one endangered bird species.

The Norton Sound environment is currently in a pristine state with no major industry and a local population of only 12,000 (OCSEAP, 1982). Disruption of the natural environment may have sociological as well as environmental impacts; the natives of this area depend on the migrating mammals, native fisheries, and seasonal bird populations for a subsistence harvest. Some of the potential impacts from offshore oil and gas activities include the risk of oil spills in the area's harsh climate, adverse effects to the benthic biota from platform discharges, possible disruption of migratory patterns of marine mammals, and interference with the subsistence harvest of the natives.

A.3.1 Physical Setting

Norton Sound is a shallow region ranging in depth from 5 m (16.4 ft) in Inner Norton Sound to 50 m (164 ft) north of St. Lawrence Island and in the Bering Strait channel. The deepest point in the proposed lease area is 27 m (88.6 ft) and the average depth is about 17 m. The sea floor slopes gradually westward from the Yukon Delta which results in a broad, heavily vegetated, intertidal zone that is often miles wide.

The climate of the area is subarctic and semi-arid and four distinct seasons control migration through the area and the distribution of species native to the area. During the summer, open water in the Inner Norton Sound area lasts from July through October and exhibits distinct stratification. The relatively warm freshwater from the Yukon River and surface runoff is sufficient to overcome tidal mixing and flow into the Sound. Cold, highly saline water of the bottom layers becomes stagnant during the summer months, flushing only during storm events. Strong surface to bottom currents in outer Norton Sound result in more complete mixing of these waters than is found in the eastern portion of Norton Sound.

The autumn transition period begins in October with a series of storms characterized by winds from variable directions, and is the most likely time for storm surges to occur. The entire Norton Sound area is vulnerable to these storm surges which can cause a rise in sea level of 5 m (16.4 ft) above tidal maximum (BLM, 1982). As the season progresses the storm tracks begin to shift south as the winds become northerly. Ice begins to form in the eastern Sound during late October. Also beginning in October, the pack ice edge in the Chukchi Sea reverses direction and is transported through the Bering Strait to the western portion of Norton Sound and the Bering Sea.

Winter lasts from January through April and is characterized by a relatively complete ice cover over the Sound. The various ice formations of Norton Sound include shorefast, Norton Sound pack ice, and Bering Sea pack ice which move into the area, each of which affects wildlife distribution and migratory patterns, and could cause damage to offshore structures.

Spring transition generally lasts from May to June and is a period of rapid warming during which the ice quickly disappears. Early weather systems parallel the Alaskan coast and push the Bering Sea ice pack northward through the Bering Strait and into the Chukchi Sea. These lead systems are major migration corridors for marine birds and mammals.

A.3.2 Phytoplankton and Benthos

Primary productivity in Inner Norton Sound is low due to turbidity from the sediment load carried by the Yukon River.

The eastern sector of Inner Norton Sound is characterized by large amounts of detrital organic carbon from the Yukon River. The soft organic sediments in this area support deposit feeders (polychaete worms, small clams, etc.) and associated predators (snails, crabs, and benthic fishes). The western sector of Inner Norton Sound is also a depositional environment but sediments are continuously resuspended and redistributed by the current of the Yukon River. Species abundant in this area are those characteristic of unstable depositional environments (polychaete worms, clams, and echinoderms).

Primary productivity of Outer Norton Sound is high. There are intense phytoplankton blooms each year associated with the spring retreat of the ice sheet. Sedimentation rates are lower, currents are more vigorous, and the benthic organisms are dominated by suspension feeders.

Norton Sound supports a rich benthic community which plays a key role in an extended food chain supporting a wide range of marine mammals. Any disruption of this benthic base could seriously affect the biota of the entire region. The invertebrate benthos are dominated by echinoderms (especially the starfish _Asterias amurensis_) which represent 80 percent of the invertebrate biomass and 60 percent of the combined invertebrate and demersal fish biomass. Gastropod mollusks are the most abundant invertebrate of potential commercial importance. Two species of king crabs are also present in sufficient numbers to support a commercial fishery. The red king crab (_Paralithodes platypus_) and the blue king crab (_Paralithodes camtschatica_) dominate the western and eastern basins, respectively (OCSEAP, 1982).

A.3.3 Fishes and Fisheries

Despite the large quantity of benthos, bottomfish are less abundant in Norton Sound than in other Alaskan regions. Cod and flatfish comprise over 75 percent of the demersal fish biomass (OCSEAP, 1982). Saffron cod, Arctic cod, and starry flounder are the most abundant demersal fish in the area; other species present are the short-horned sculpin, yellowfin sole, and Alaskan plaice. These six species are important food sources for marine mammals and may be used by man as subsistence species.

Five species of salmon (chum, pink, coho, chinook, and sockeye) are also found in the Norton Sound area. Commercially, the most important pelagic species is the Pacific herring. These fish spawn in the subtidal regions of Norton Sound, where the pelagic larvae remain in the subtidal region for up to two months (BLM, 1982). Other common pelagic fish species are rainbow smelt, capelin, and the Pacific sandlance. The sandlance is a major item in the diet of surface-feeding seabirds.

A.3.4 Birds

The Norton Sound lease area is adjacent to the major northern Bering seabird colonies and offshore bird concentration areas. At least 5 million breeding seabirds, or 23 percent of Alaska's nesting population occur in this area (BLM, 1982). The lease area is adjacent to one of the most important and productive waterfowl and shorebird habitats in North America. During the summer season the seabirds are concentrated in the large breeding colonies of St. Lawrence Island, the Diomedes, and the Bluff Cliffs east of Nome. Most, but not all, of these birds migrate south in October.

The birds of prey in the Norton Sound area include falcons (e.g., gyrfalcon), owls (e.g., snowy owl), hawks (e.g., marsh hawk), and the golden eagle. Nesting areas for the birds of prey are associated with major seabird colonies upon which they depend as food sources. These birds, including the endangered Peregrine falcon, also migrate south in September and October.

A.3.5 Marine Mammals

Marine mammal species that are strongly associated with seasonal sea ice will be found in the Norton Sound area at some time during the year. Most species follow the advance of the Bering Sea ice pack in the fall and remain in the proposed lease area until the spring retreat. This would include such species as polar bear (Ursus maritimus), walrus (Odobenus yosmarus), ringed seal (Phoca hispida), bearded seal (Erignathus barbatus), spotted seal (Phoca vitulina largha), ribbon seal (Phoca fasciata), beluga whale (Delphinapterus leucas), minke whale (Balaenoptera acutorostrata), and killer whale (Orcinus orca).

Five endangered species of whales occur to a varying degree in or near the proposed lease area. In general, they all remain in western Norton Sound and the Bering Sea:

- Bowhead whale (Balaena mysticetus)
- Gray whale (Eschrichtius robustus)
- Black whale (Megoptera novaeangliae)
- Fin whale (Balaenoptera physalus)
- Sei whale (Balaenoptera borealis)

A.3.5.1 Administrative Context

OCS oil and gas Lease Sale No. 57 covers the Norton Sound area. In addition to this Federal lease sale, the State of Alaska 5-Year Oil and Gas Leasing Schedule also lists an offshore sale in Norton Sound (Sale No. 38). USGS estimated that for Lease Sale No. 57, at the peak of exploratory drilling, an estimated 5 drilling rigs would complete 13 wells. If exploratory drilling is successful, the developmental period may include as many as 172 production wells operating from nine production platforms (BLM, 1982).

The Atlantic-Richfield Company put in a Continental Offshore Stratigraphic Test (COST) well on June 7, 1982, for which it was issued a single discharge permit. The EPA has issued a general NPDES permit to cover exploratory drilling activity in this area.

A.3.6 Potential Impacts from Drilling Activity

The greatest danger from offshore oil and gas activity in Norton Sound appears to be that of an oil spill. The chance of such an accident occurring is magnified by the environmental hazards unique to Norton Sound.

The Final EIS concluded that the large sediment load from the Yukon would mask any deposition of drilling discharges (BLM, 1982), which may also be the case for lease blocks that lie in the deposition zone for the Yukon River. The Yukon River deposits between 70 and 90 million metric tons of sediment into Norton Sound each year. However, insufficient oceanographic information is available to determine the extent of this zone or the deposition patterns for Yukon sediment throughout the proposed lease areas.

Available information on water quality in Norton Sound (BLM, 1982) indicates background levels of toxic metals to be one and two orders of magnitude less than the applicable EPA water quality criteria. Sediment analyses show hydrocarbons present only in concentrations typical of biogenic origin. There is no evidence of petroleum hydrocarbons in either the water column or the sediments. Thus, the area is considered to be in a pristine state.

Potential impacts to the benthos would be significant, but it is not possible to evaluate this threat based on currently available data. Another factor to be considered in assessing the environmental impacts from drilling discharges is the susceptibility of the area to periodic storm surges. These events could, by redistributing localized platform discharges, consequently redistribute the zone of impact.

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